Challenges in computing thermal and non-thermal emission from relativistic outflows

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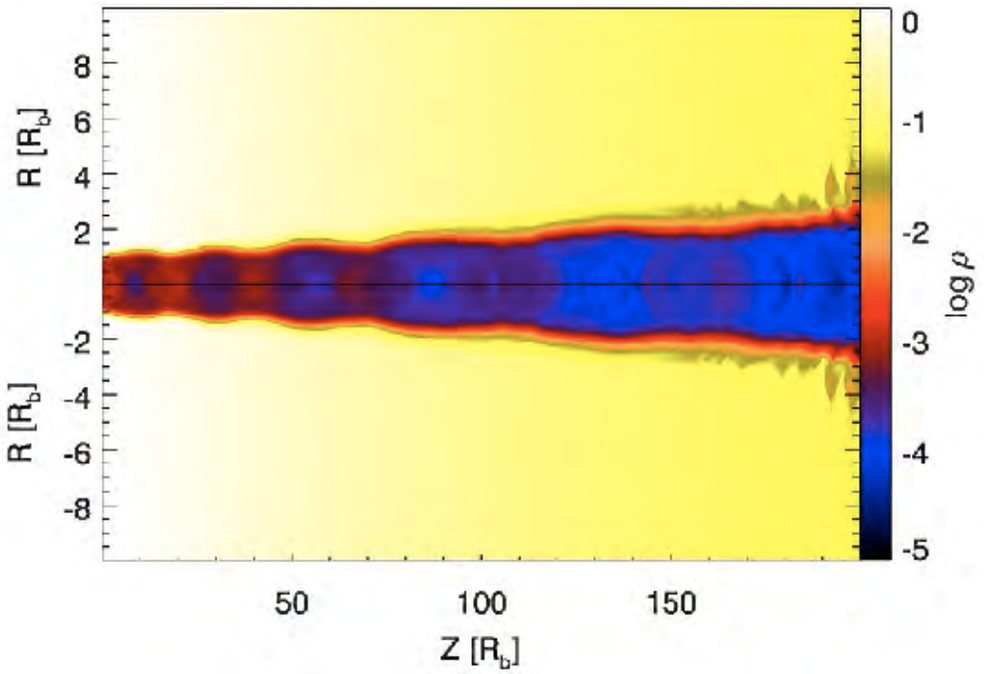
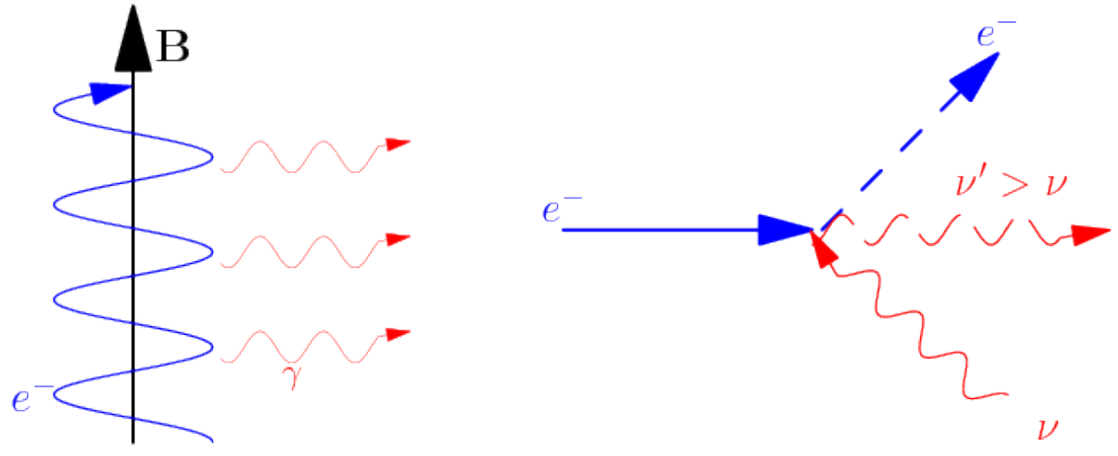
Outline

1. Simulating relativistic jets
2. Jets from tidal-disruption events
3. Jets in blackbody dominated GRBs
4. Summary

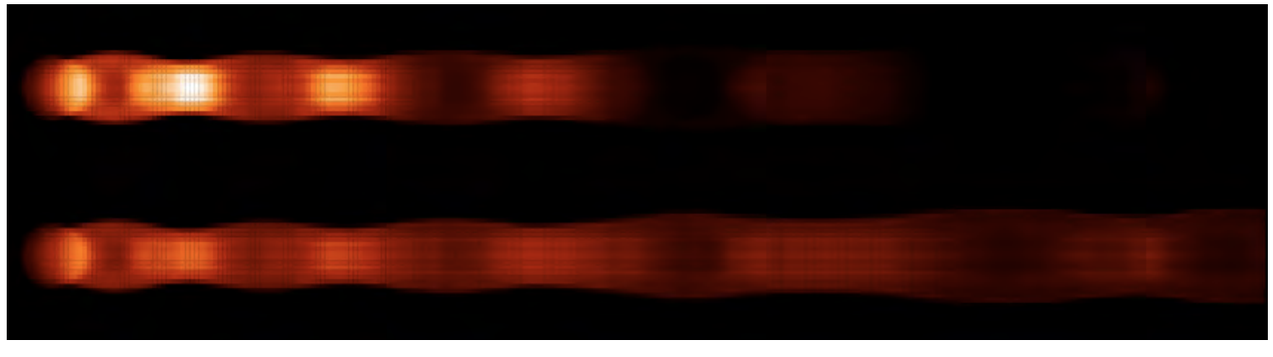
Simulating relativistic jets



1. relativistic hydrodynamics simulation
   - finite-volumes
   - method of lines
   - shock-capturing
   - approximate Riemann solver



2. non-thermal particle evolution
   - phenomenological shock acceleration
   - radiative and adiabatic loses
   - semi-analytic electron-kinetic eq. solver
   - spatial advection

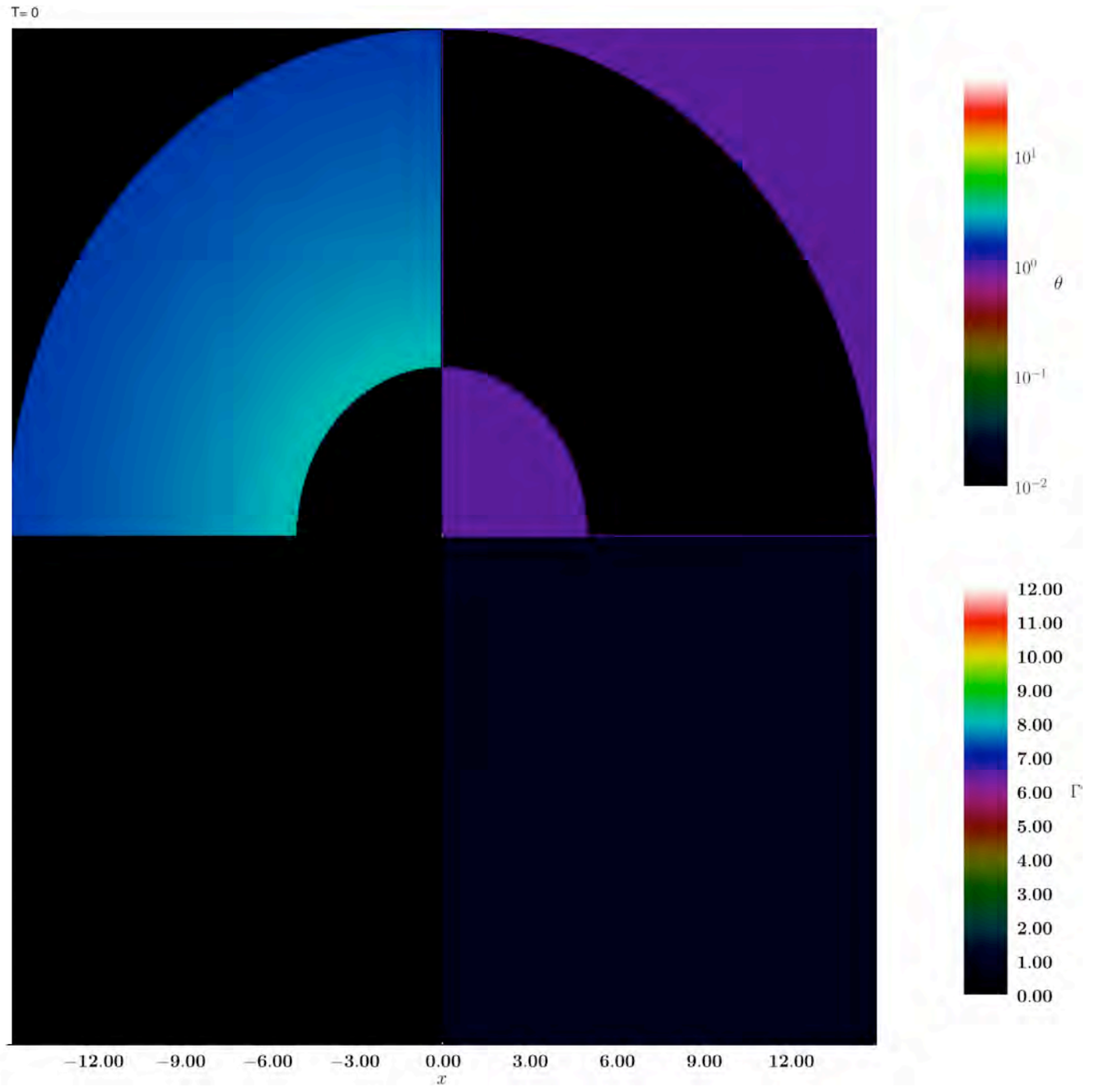


3. radiative transfer
   - time-dependent emission and absorption
   - relativistic effects (beaming, Doppler)
   - light-travel times
   - synchrotron, inverse-Compton scattering

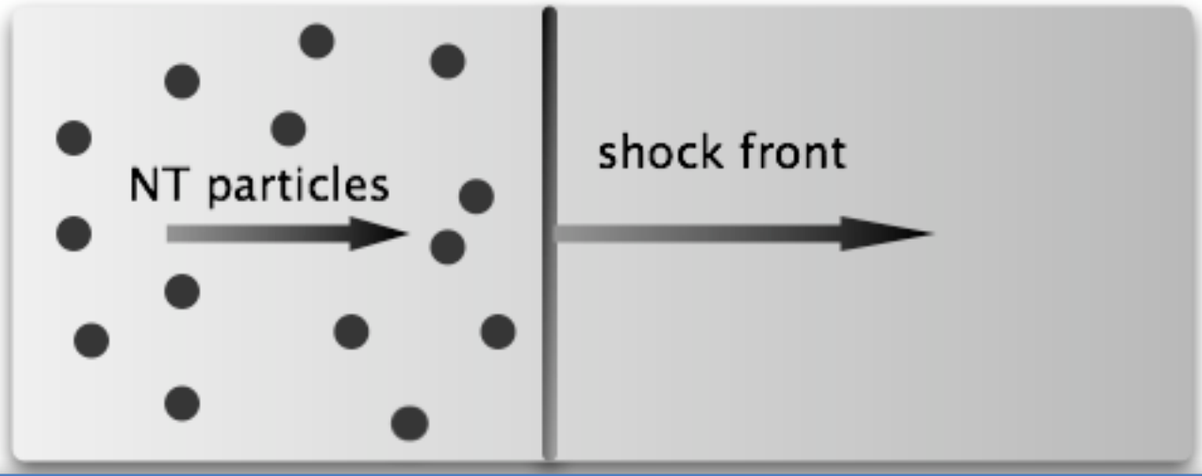
MRGENESIS

MRGENESIS (Aloy *et al.* '99 ApJS , Leismann *et al.* '05, A&A, Mimica *et al.* '07, '09 A&A)

- finite volume approach
- method of lines: separate semi-discretization of space and time
- time advance: TVD Runge-Kutta methods of 2nd and 3rd order
- high-resolution shock-capturing scheme
- inter-cell reconstruction: PPM
- numerical fluxes: Marquina, HLLE, HLLC
- RMHD: constraint transport to conserve $\nabla \mathbf{B}$
- orthogonal coordinate systems: Cartesian, cylindrical, spherical
- MPI + OpenMP: scales up to 10K cores
- HDF5 library for parallel I/O



Non-thermal particles



- model: relativistic shocks accelerate electrons to high energies
- phenomenological source term:

$$Q(\gamma) = Q_0 \gamma^{-s};\ \gamma_{\rm min} \le \gamma \le \gamma_{\rm max}$$

$$\gamma := \left(1 - v^2/c^2\right)^{-1/2}$$

electron-kinetic equation

$$\frac{\partial n(\gamma,t)}{\partial t} + \frac{\partial}{\partial \gamma}\left(\dot{\gamma}\ n(\gamma,t)\right) = Q(\gamma)$$

particle energy losses/gains:

$$\dot{\gamma} = k_a \gamma - k_s \gamma^2$$

adiabatic compression or expansion

$$k_a = \frac{1}{3}\frac{\mathcal{D}\ln\rho}{\mathcal{D}t}$$

synchrotron losses

$$k_s = -\frac{4\sigma_T B^2}{3 m_e^2 c^2}$$

cooling break:

$$\gamma_{\rm c}(t) = \frac{1}{k_s t}$$

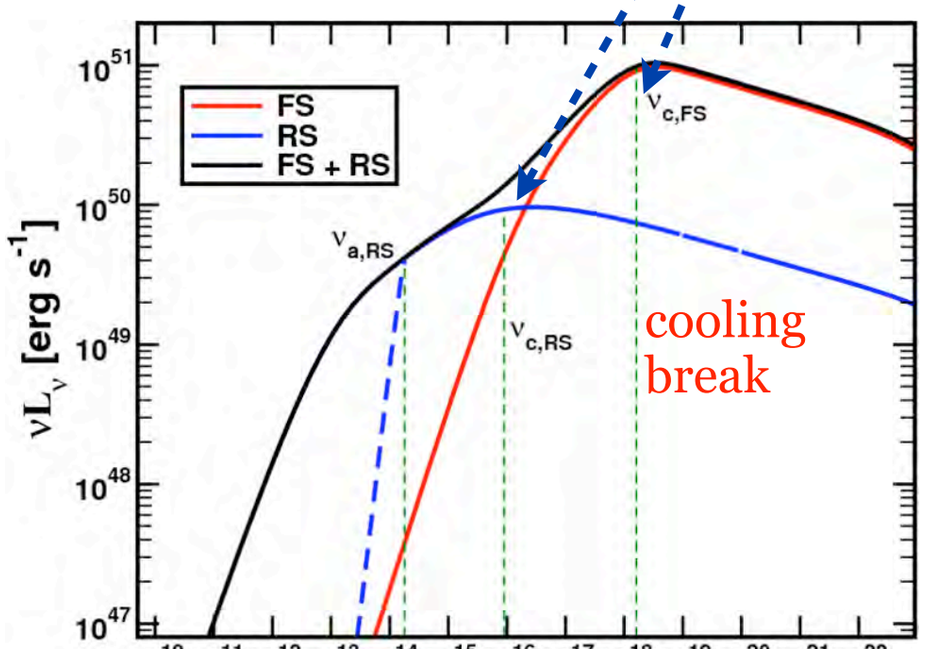
fast adaptive bins solver (conserves particle number):

$$\gamma_i(t) = \gamma_i(0) e^{k_a t}\left[1 + \gamma_i(0)\frac{k_s}{k_a}\left(e^{k_a t} - 1\right)\right]^{-1}$$

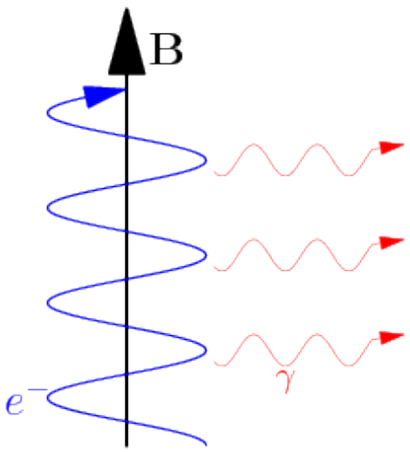
$$n(\gamma_i,t) = n(\gamma_i(0),t) e^{2k_a t}\left[1 + \gamma_i(0)\frac{k_s}{k_a}\left(e^{k_a t} - 1\right)\right]^{2}$$

$$\mathcal{N}(\gamma_i,\gamma_{i+1},t) := \int_{\gamma_i}^{\gamma_{i+1}} {\rm d}\gamma\ n(\gamma,t)$$

$$= e^{3k_a t}\mathcal{N}(\gamma_i(0),\gamma_{i+1}(0),t)$$



Synchrotron radiation



synchrotron emissivity: $j(\nu) = \dfrac{\sqrt{3}e^3}{4\pi m_e c^2}\, B \int \mathrm{d}\gamma\; n(\gamma)\; R\left(\dfrac{\nu}{\nu_0 \gamma^2}\right)$

$$\nu_0 = \frac{3e}{4\pi m_e c}\, B \qquad n(\gamma) = n(\gamma_{\min}) \left(\frac{\gamma}{\gamma_{\min}}\right)^{-q} \;;\; \gamma_{\min} \le \gamma \le \gamma_{\max}$$

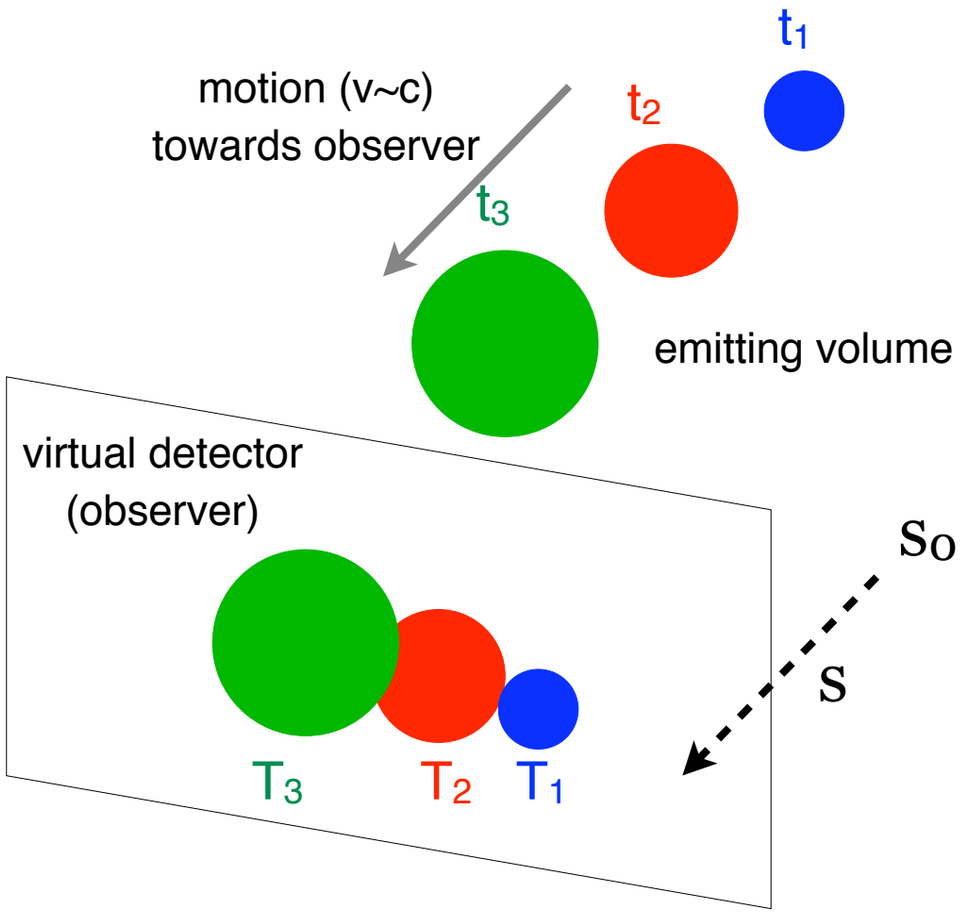
$$R(x) = \frac{1}{2}\int_0^\pi \mathrm{d}\alpha\; \sin^2\alpha\; F\left(\frac{x}{\sin\alpha}\right) \qquad F(x) = x\int_x^\infty \mathrm{d}\xi\; K_{5/3}(\xi)$$

$$j(\nu) = \frac{\sqrt{3}e^3 B}{8\pi m_e c^2}\; n(\gamma_{\min})\gamma_{\min}^q \left(\frac{\nu}{\nu_0}\right)^{(1-q)/2} H\left(\frac{\nu}{\nu_0 \gamma_{\min}^2}, q, \frac{\gamma_{\max}}{\gamma_{\min}}\right)$$

interpolation of the function: $H(x,q,\eta) = \displaystyle\int_{x/\eta^2}^{x} \mathrm{d}\xi\; \xi^{(q-3)/2}\; R(\xi)$

- advantage: synchrotron computation cost reduced by a factor 50-100
- tradeoff: large interpolation table (2GB) needs to reside in RAM

Radiative transfer



- for a fixed observer time T, need to process the **whole** spacetime evolution to compute a **single** virtual image
- tightly coupled, highly non-local problem
- **5D problem**:
  - virtual detector image **(x, y)**
  - observation time **T**
  - observation frequency **ν**
  - contributions along the line of sight **s**

radiative transfer equation:

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu + \alpha_\nu I_\nu$$

synchrotron, inverse-Compton

synchrotron self-absorption

I_ν : intensity j_ν α_ν : emission, absorption

T : observer time t : jet evolution time

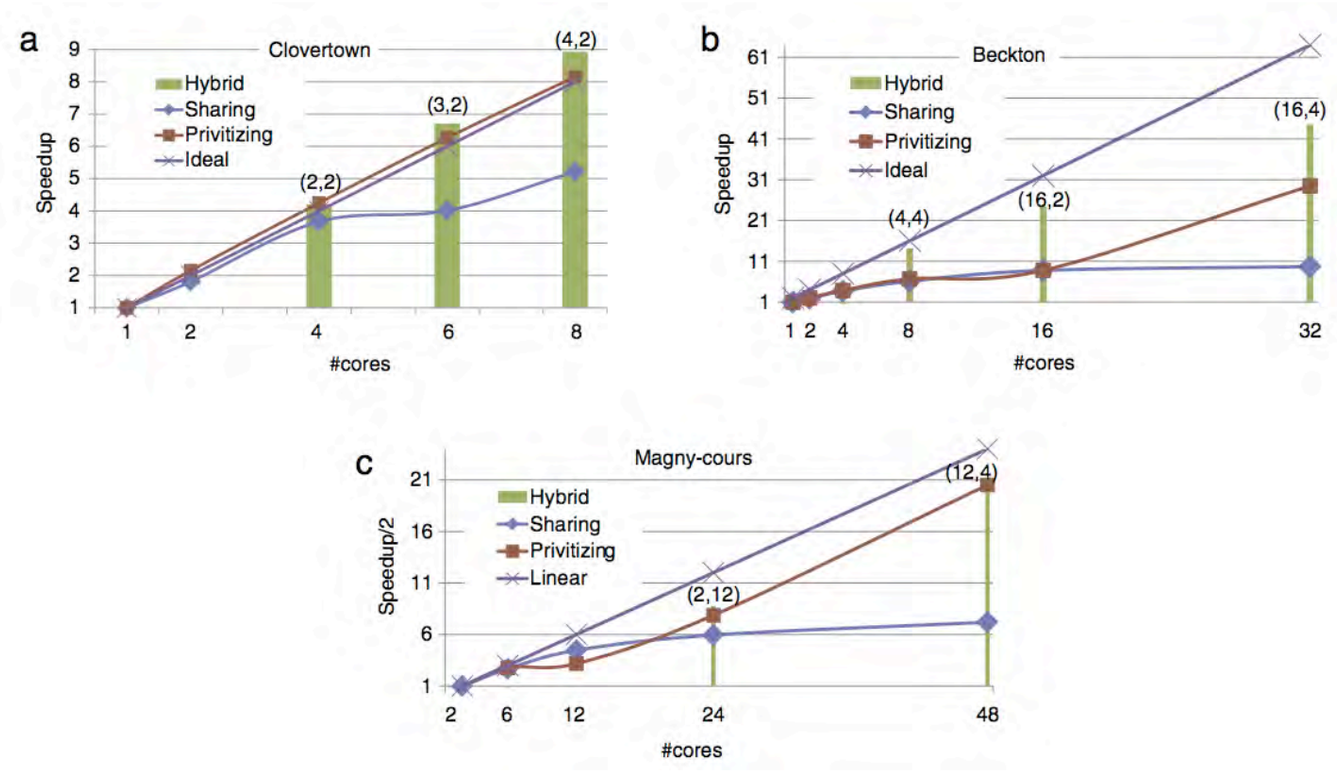
s : path towards the detector

$$s = c(t - T) + s_0$$

for a fixed *T*, equation gives an isochrone *(s, t)* along each line of sight

*SP*ectral *EV*olution code

- SPEV (Mimica et al., Astrophysical J. **696** (2009) 1142) :
  - non-thermal electron transport and evolution equations
  - time- and frequency-dependent radiative transfer in a dynamically changing background
  - parallelization: MPI (over detector pixels), OpenMP (over particles)



S. Tabik *et al. Computer Physics Communications* ***183*** *(2012) 1937*

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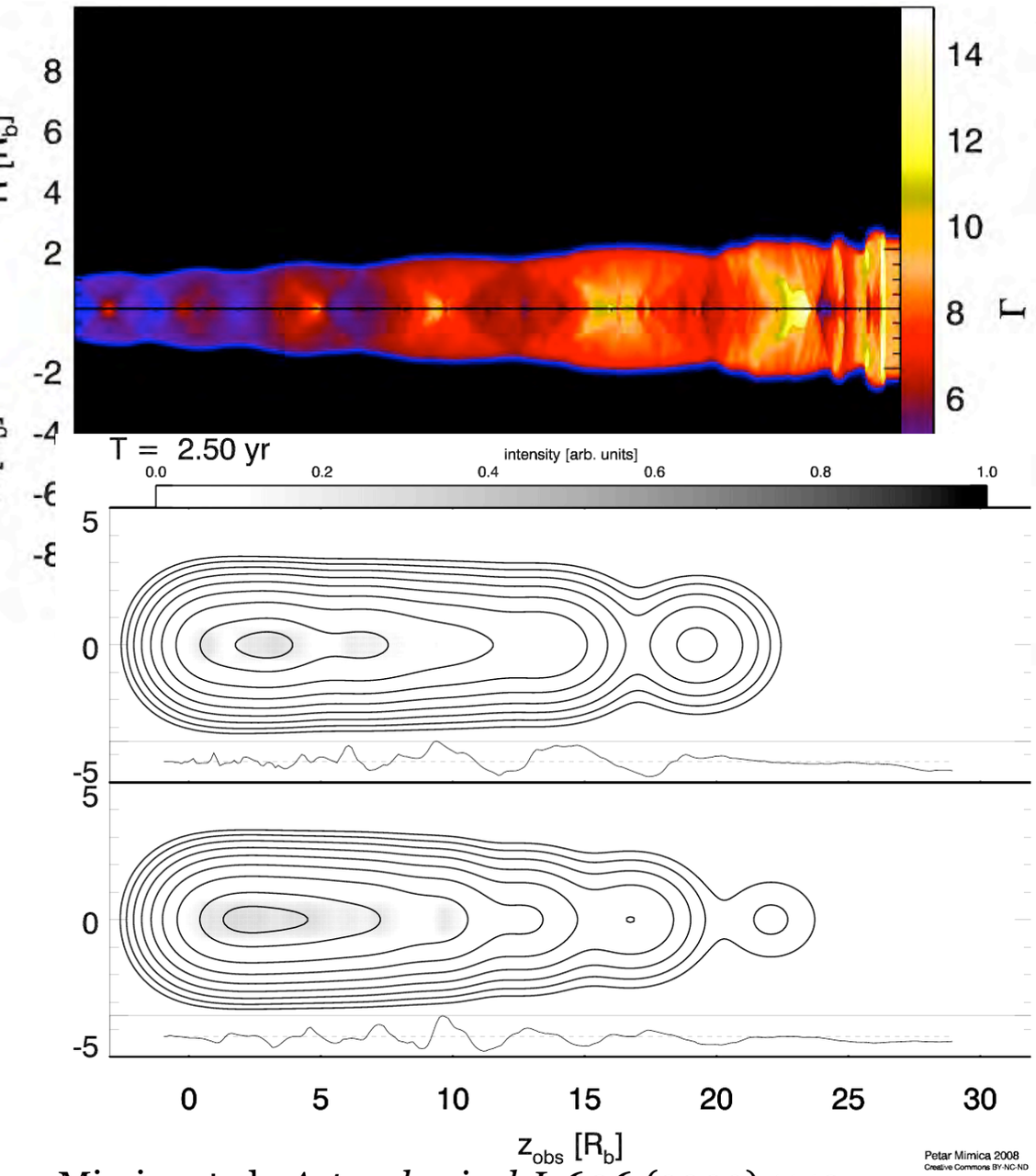

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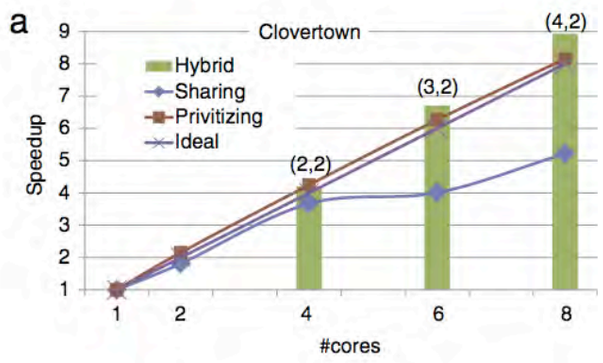

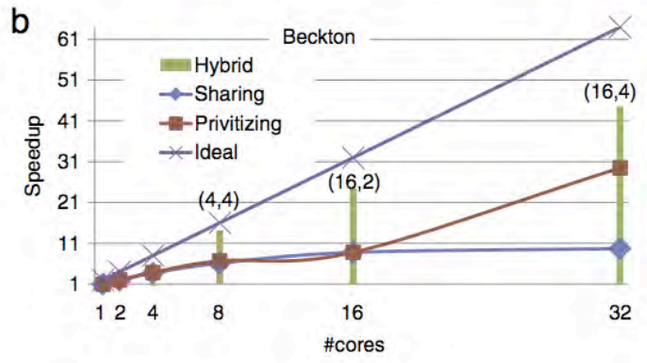

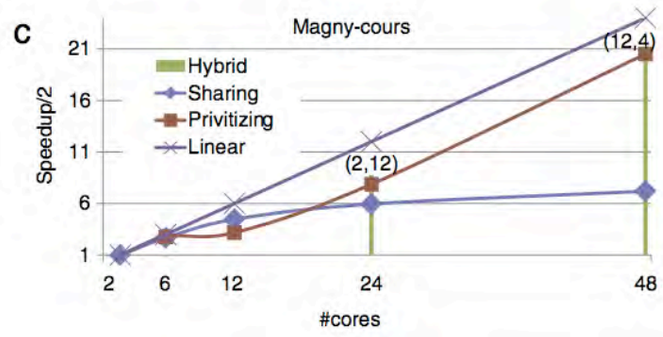

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Simulation building blocks

Depending on the application, select one from each row:

RMHD
(GRBs, blazars)

RHD
(AGN jets, TDE jets)

exact Riemann solver
(blazar, GRB internal shocks)

+

3D transport & evolution
(radio maps, off-axis light curves)

Cylindrical
(blazar internal shocks)

Spherical
(on-axis GRB blast wave)

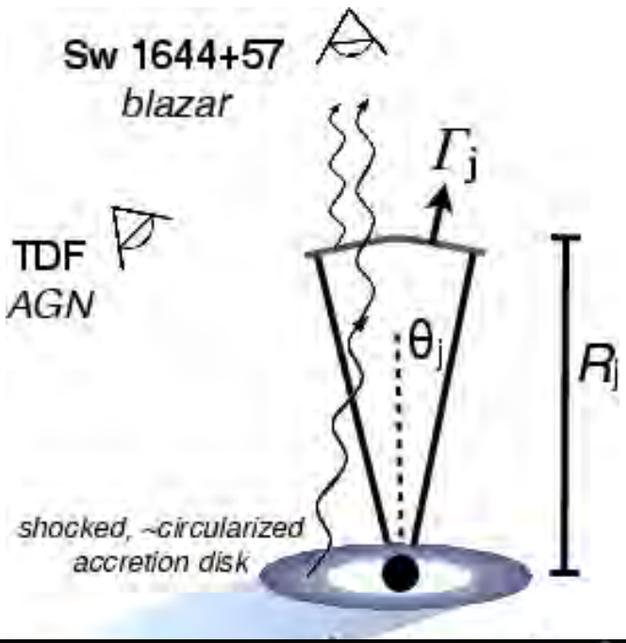
+

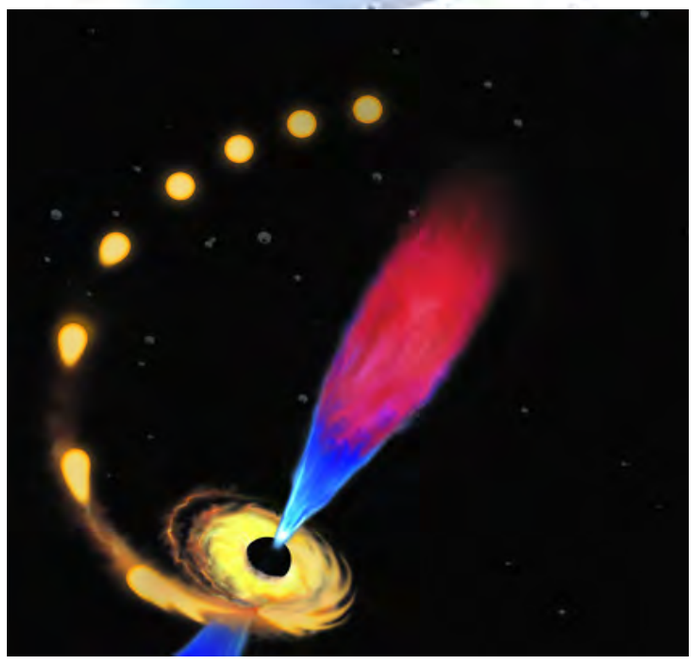
Synchrotron (+ EC)
(radio maps, blazar X light curves, GRB afterglows, TDE radio transients)

Synchrotron self-Compton
(blazar radio-to-γ-ray light curves and spectra)

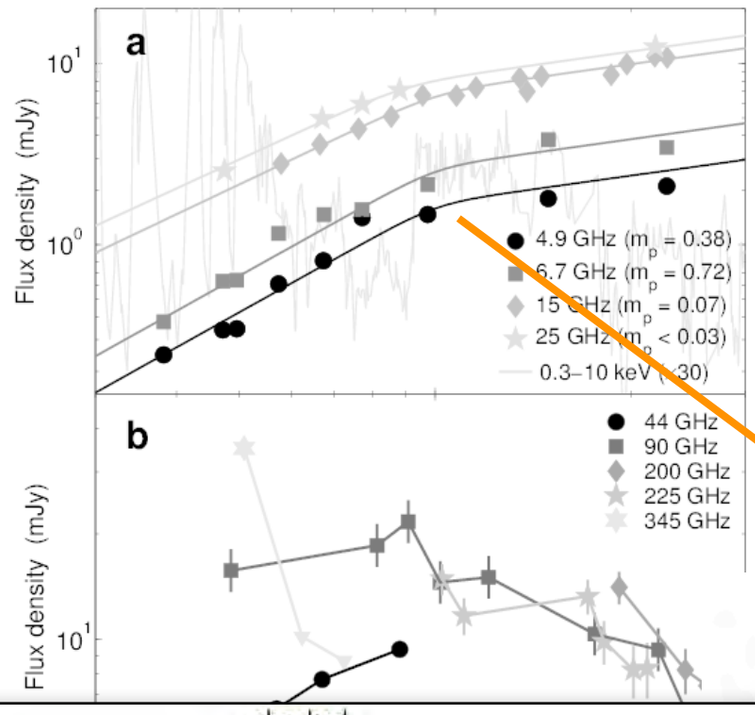
Swift J1644+57

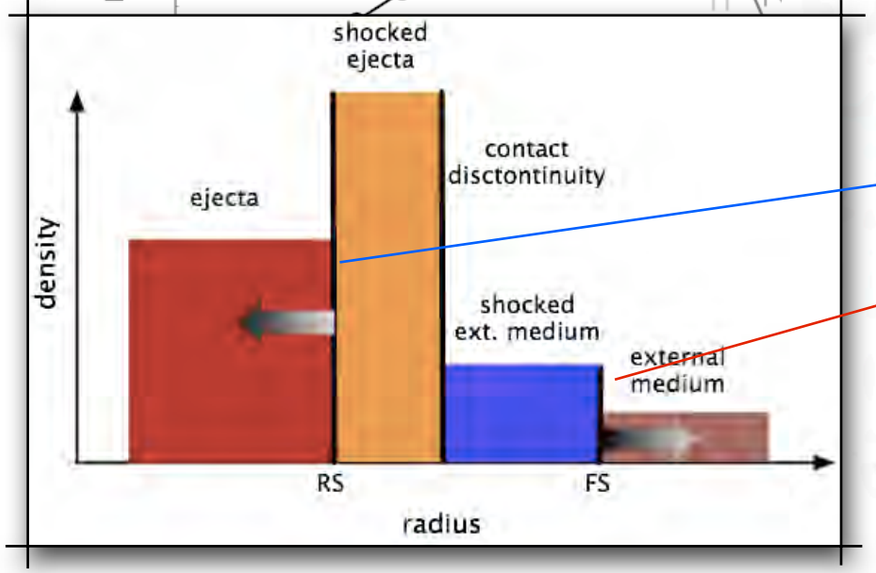
- Swift J164449.31573451 (z = 0.354), initially identified as GRB110328A
- longevity of its afterglow points to a different explanation: a blazar-like jet fed by a tidal disruption of a solar-mass star



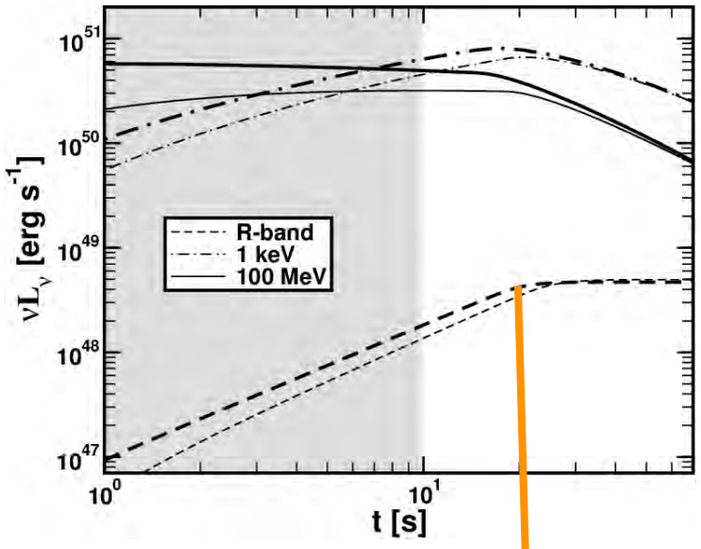


Zauderer *et al.* 2011

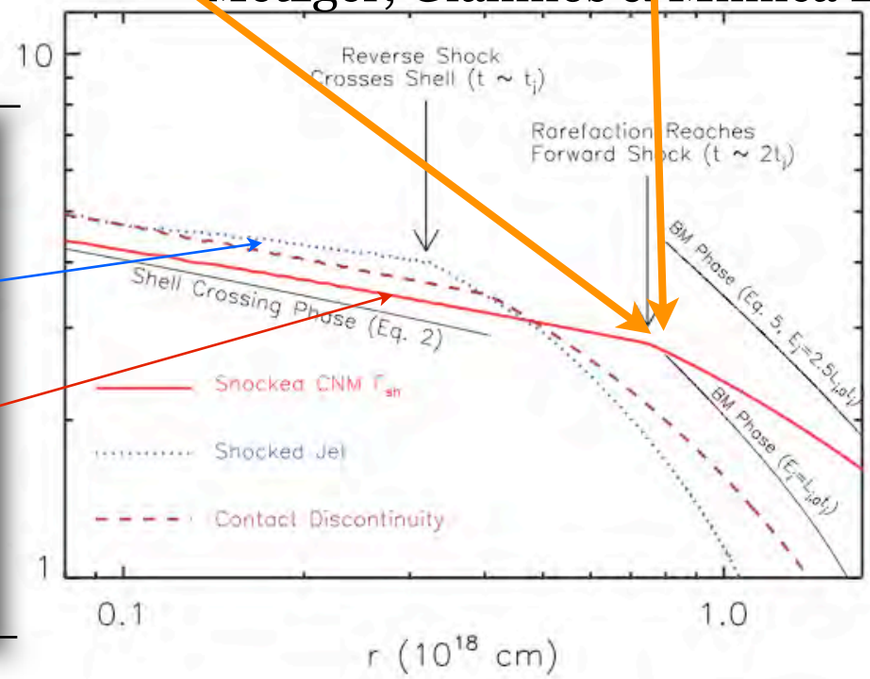




Mimica, Giannios & Aloy 2010



Metzger, Giannios & Mimica 2012



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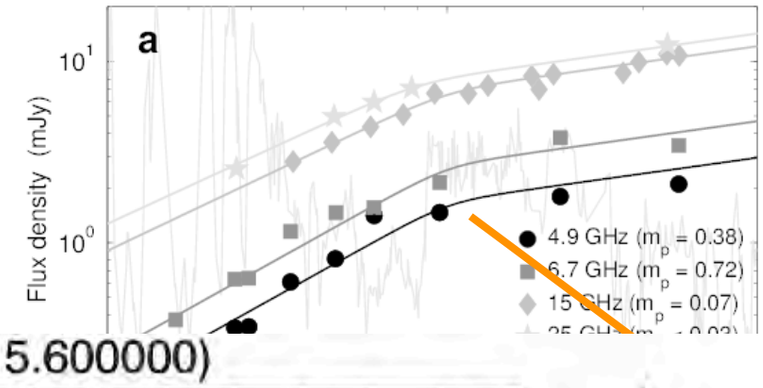

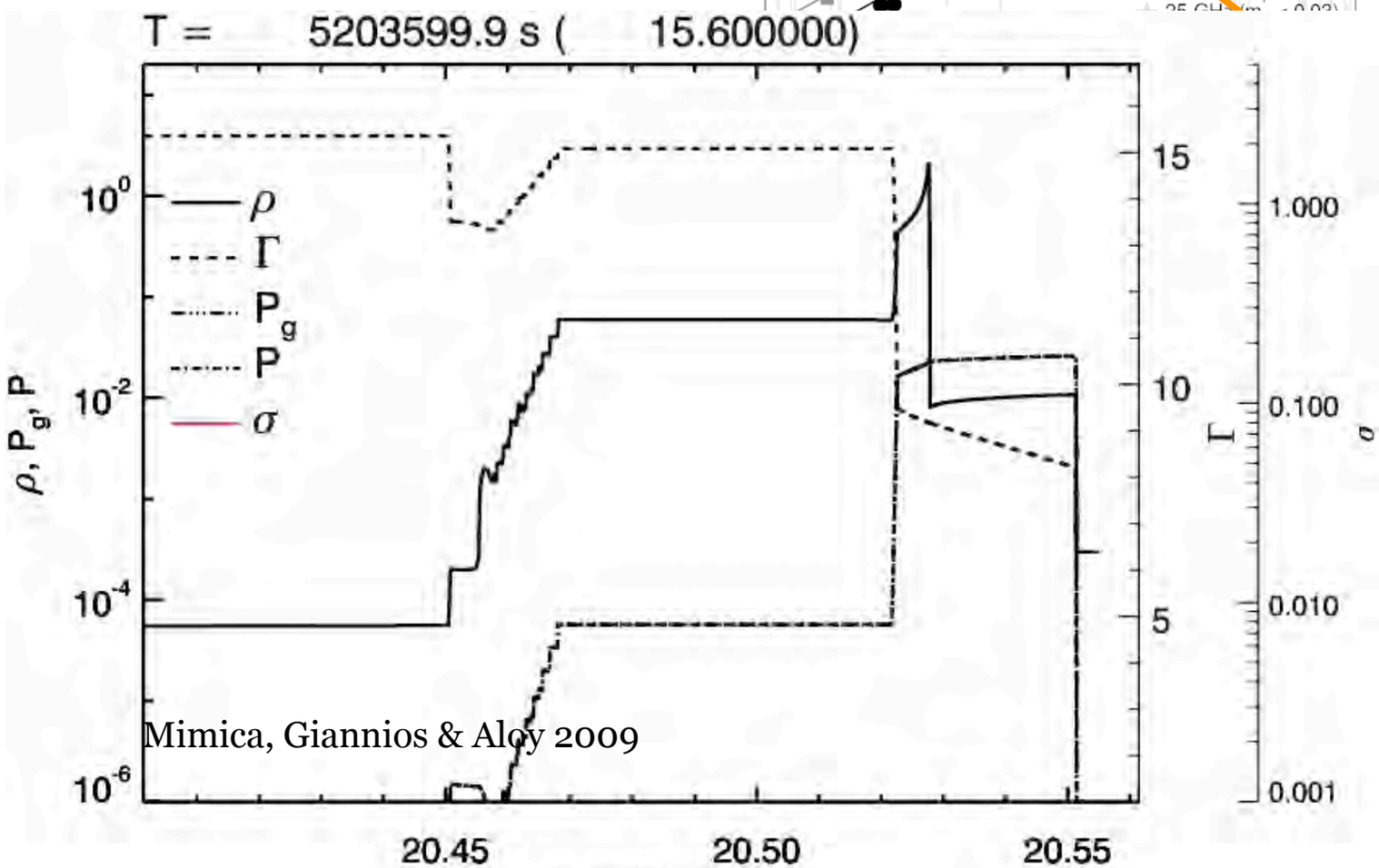

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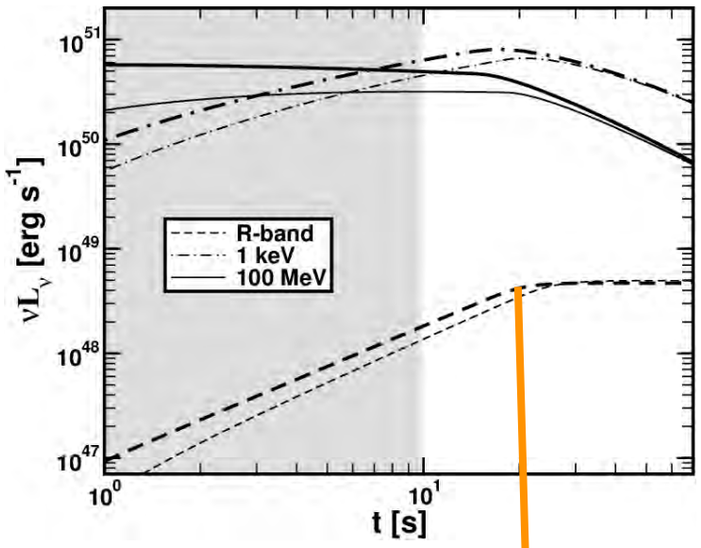
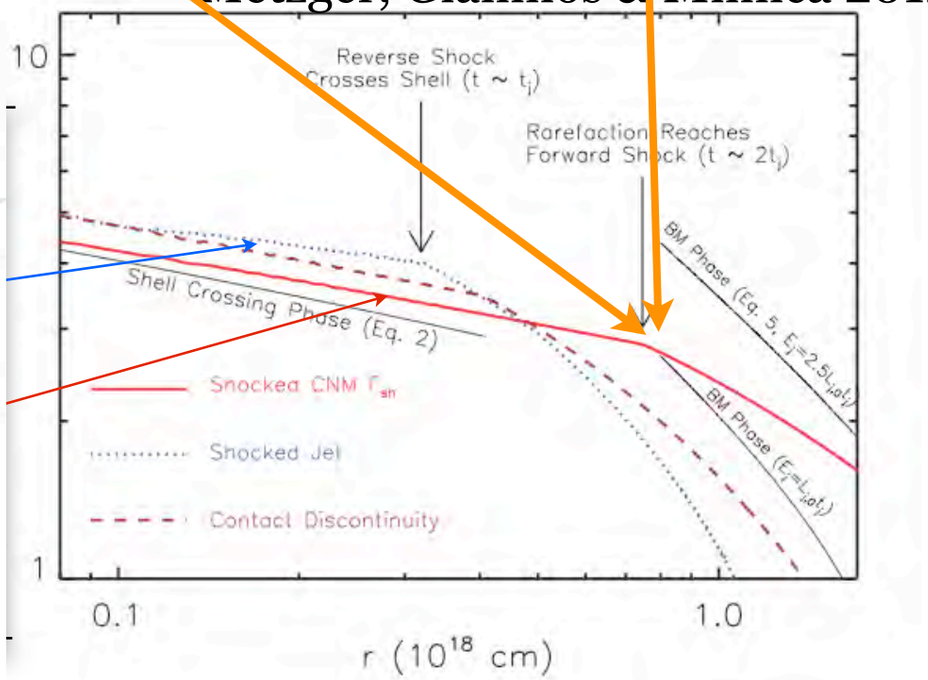


Metzger, Giannios & Mimica 2012



RHD simulations of TDE jets

Physical model

$$L_j(t) = L_{j,0}\left(\max\left[1, \left(\frac{t}{t_{j,0}}\right)\right]\right)^{-5/3}$$

$$L_{j,0} = 5 \times 10^{47}\ \mathrm{erg\ s^{-1}}$$

$$t_{j,0} = 5 \times 10^{5}\ \mathrm{s}$$

$$\Gamma_{j,0} = 5 \qquad \theta_{j,0} = 0.3\ \mathrm{rad}$$

$$\Theta_0 := \frac{P_0}{\rho_0 c^2} = 10^{-2}$$

$$\mathrm{TM\ EOS}: h(\Theta) = \frac{5}{2}\Theta + \sqrt{\frac{9}{4}\Theta^2 + 1}$$

(Mignone *et al.* 05)

$$R_{j,0} = 5 \times 10^{16}\ \mathrm{cm}$$

$$n_{\mathrm{ext}}(R) = 3.33 \times 10^{1}\ \mathrm{cm^{-3}}\left(\frac{R}{R_{j,0}}\right)^{-1}$$

$$T_{\max} \approx 15\ \mathrm{years}$$

Mimica, Giannios, Metzger & Aloy, in prep.

thermal density

Lorentz factor

non-thermal density

synchrotron peak

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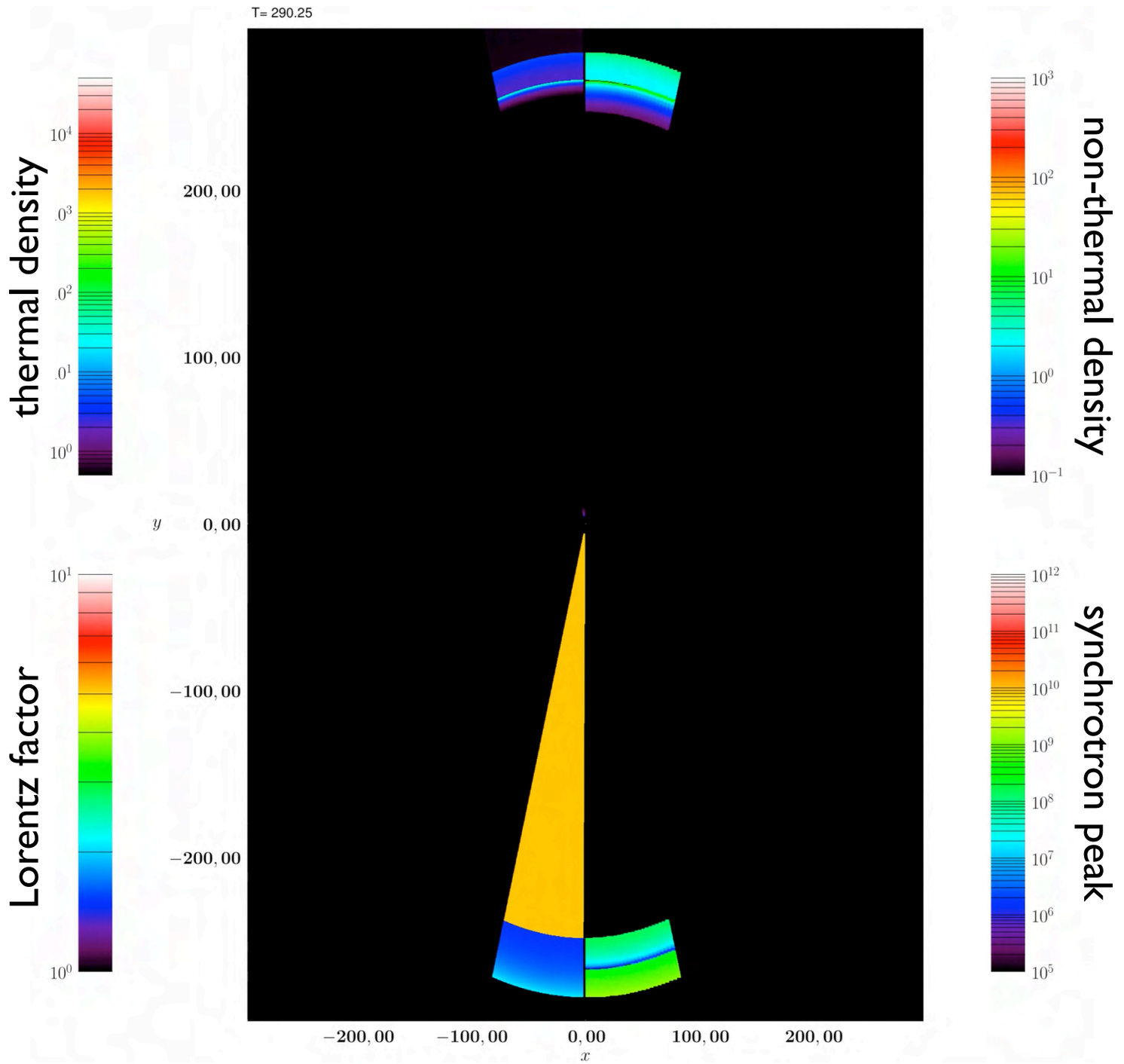

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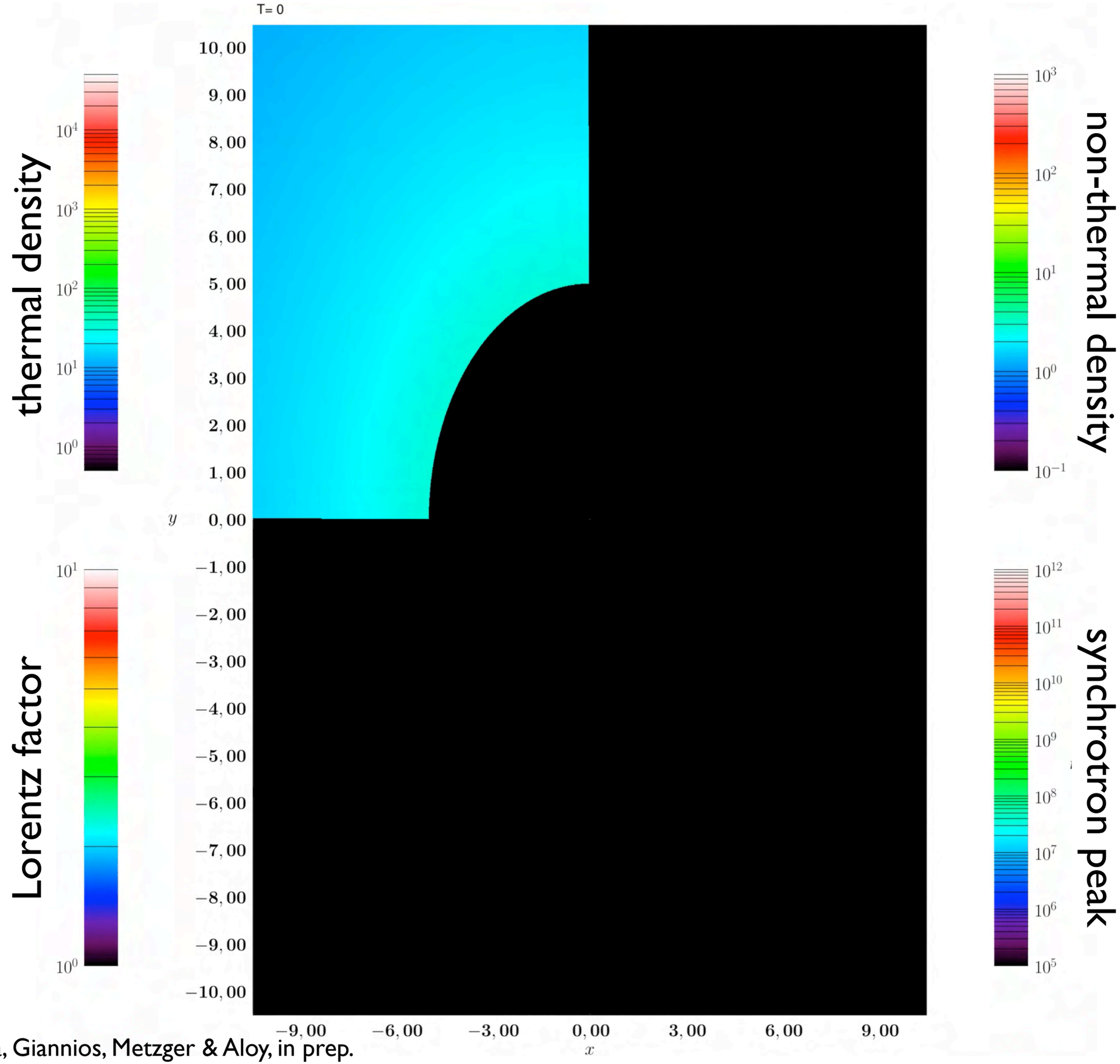
2D RHD simulation



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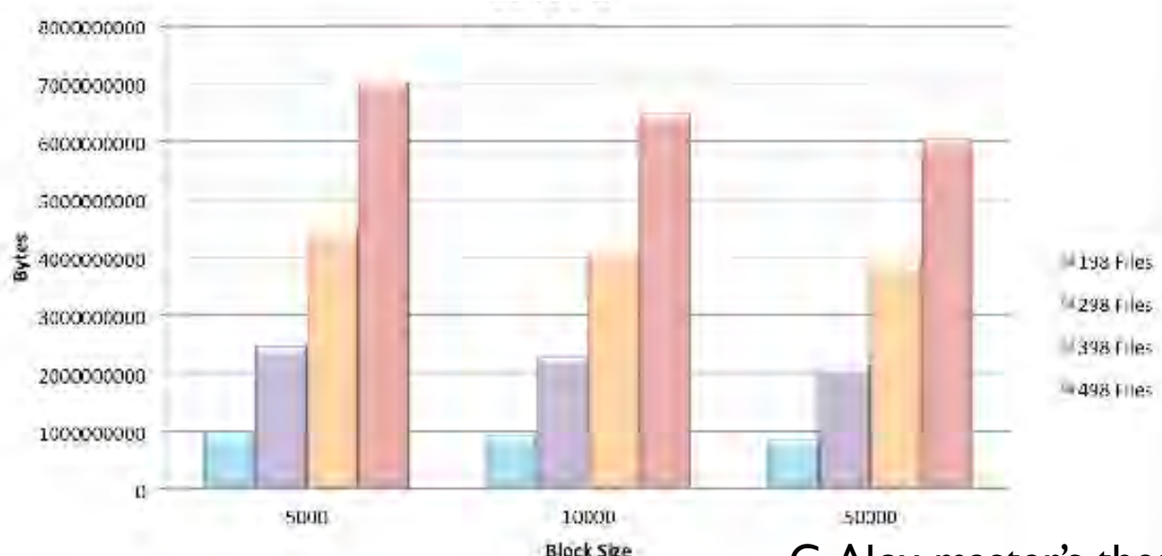
Light curves and technical details

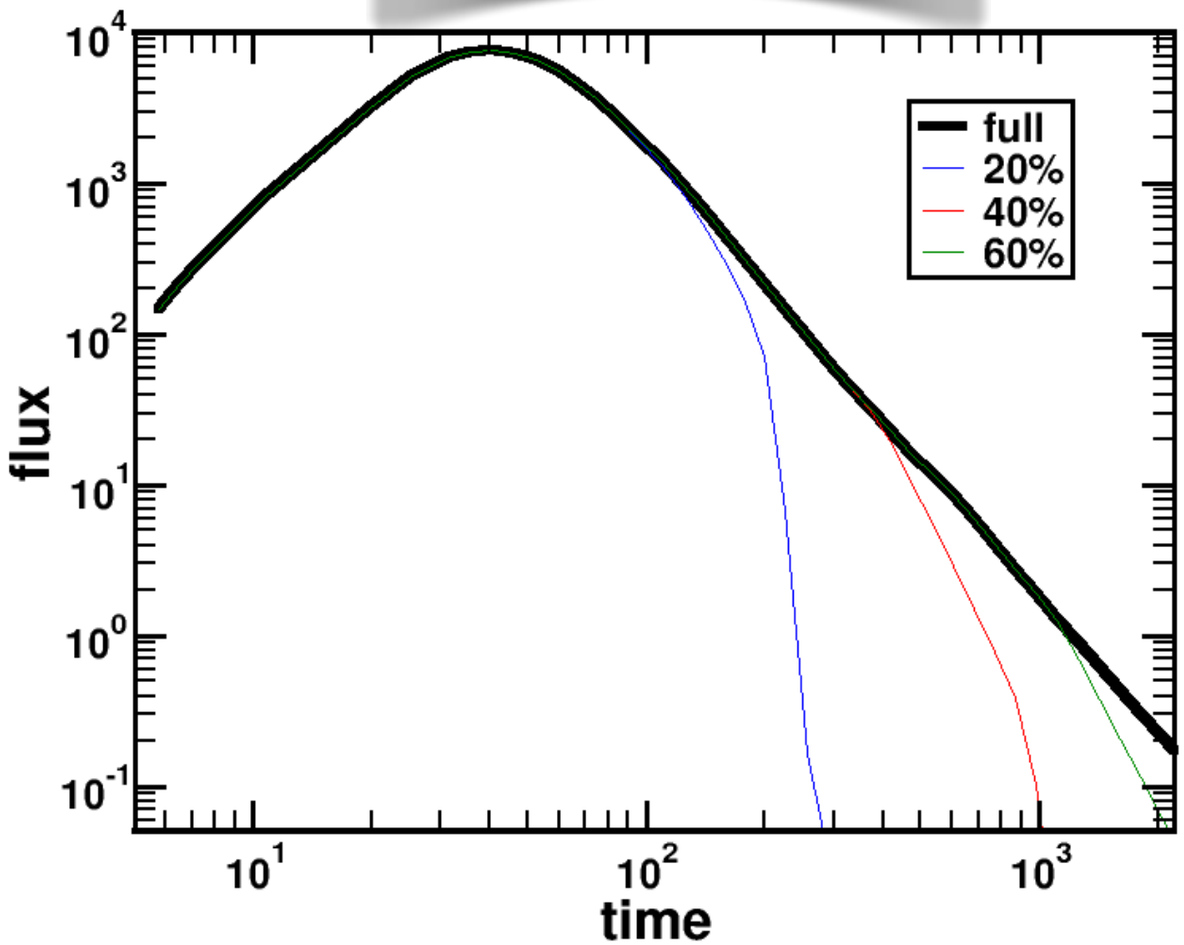
Technical details

- uniform spherical grid, 2D resolution 54000 x 250 *(12 million numerical cells)*
- 1400 snapshots: dense linear coverage (600 snap.) until 1.6 yr; progressively increasing intervals (800 snap.) 1.6 - 15 yr
- dense coverage in time necessary to correctly compute the light curves
- total res.: 54000x250x1400 = **$1.89\ 10^{10}$**
- 3D estimate: $2\ 10^{12}$ points
- tens to hundreds of GB of shared RAM (machine *LluisVives* at UV, 114 cores)
- size of the intermediate files increases quadratically with number of snapshots!



C. Aloy, master's thesis

Radio light curve



- 10^{6} non-thermal emitting regions (32 bins)
- enough space-time coverage is crucial for correct light curve computation
- extension of the duration of the light curve requires disproportionally more computation time and storage space!

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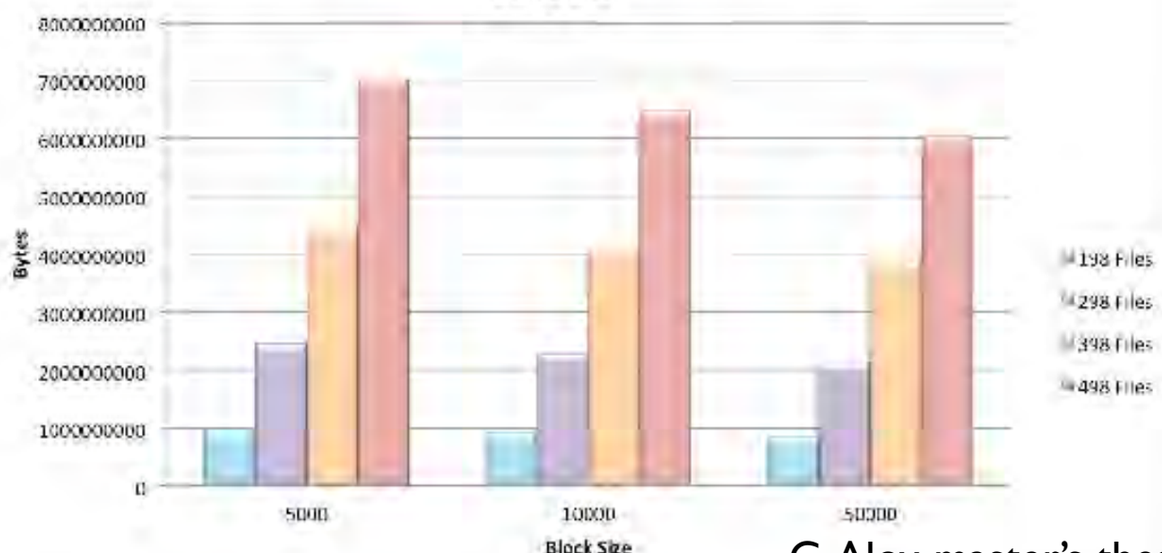

C. Aloy, master's thesis

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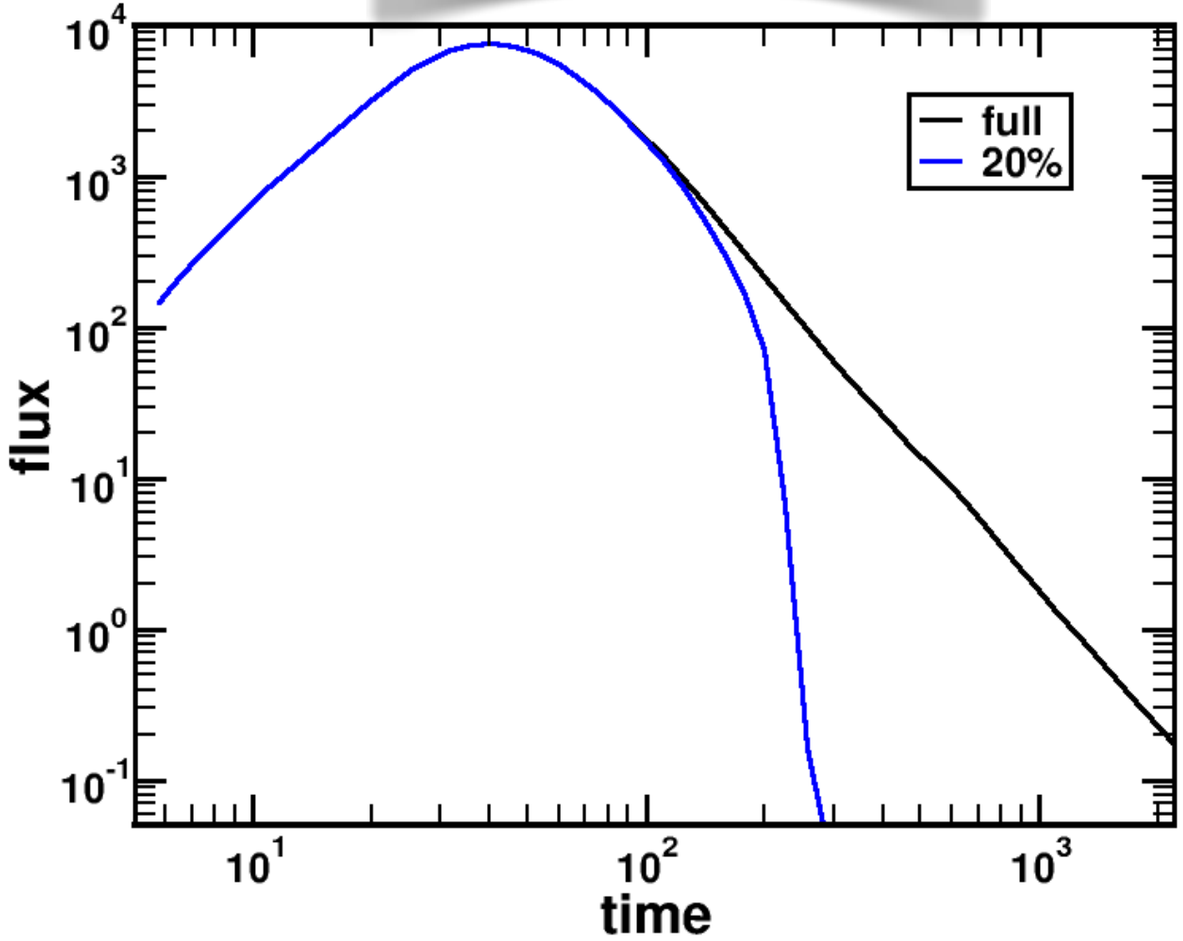

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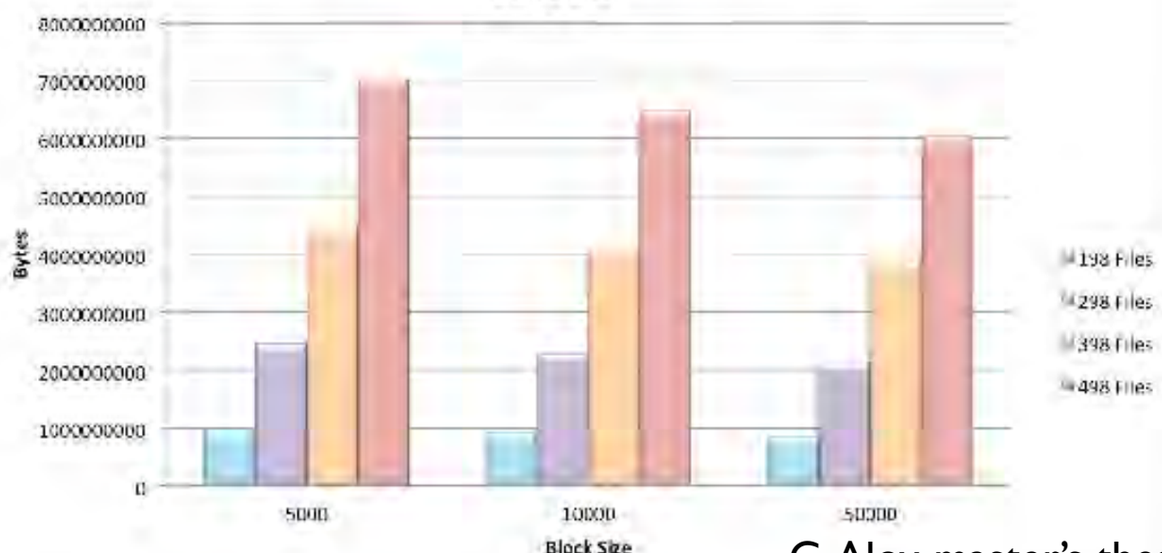

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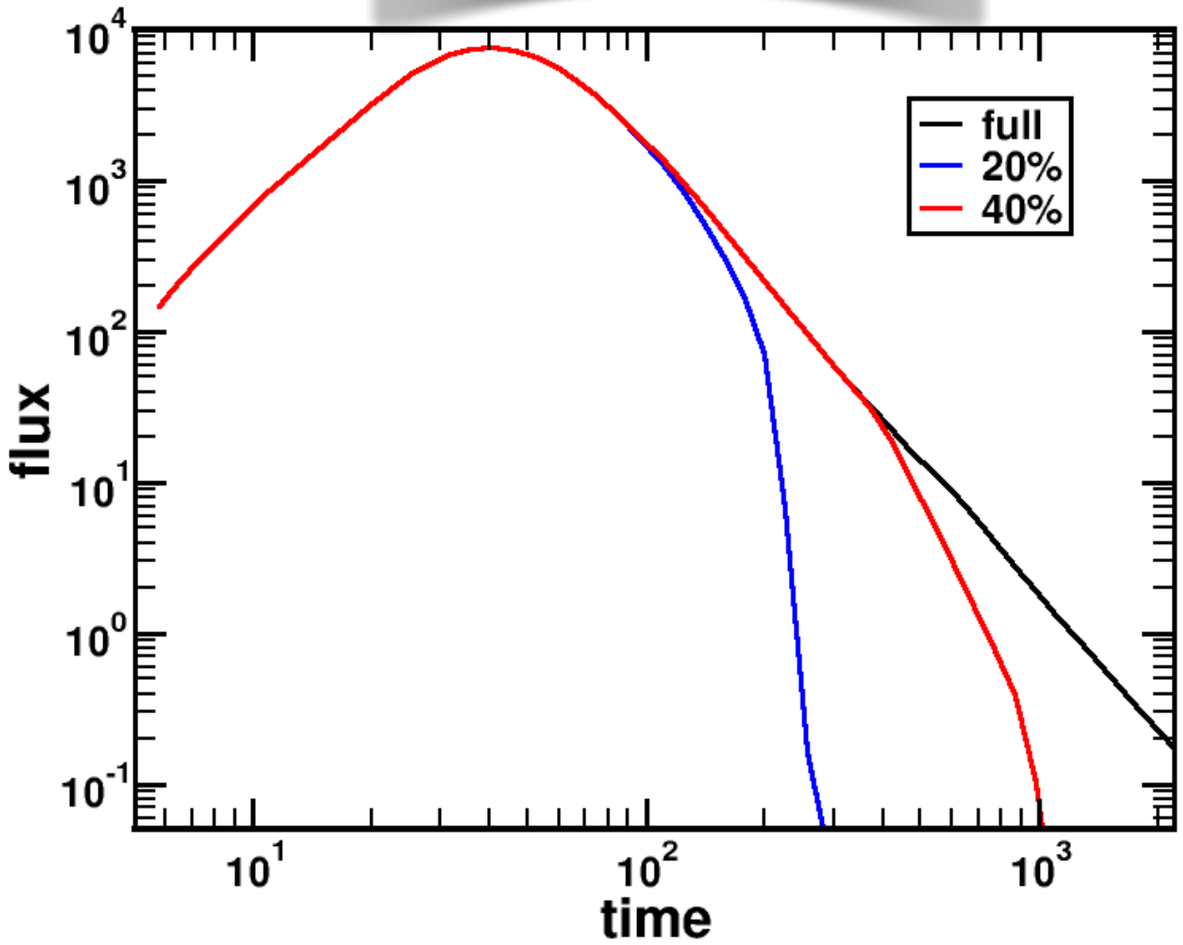

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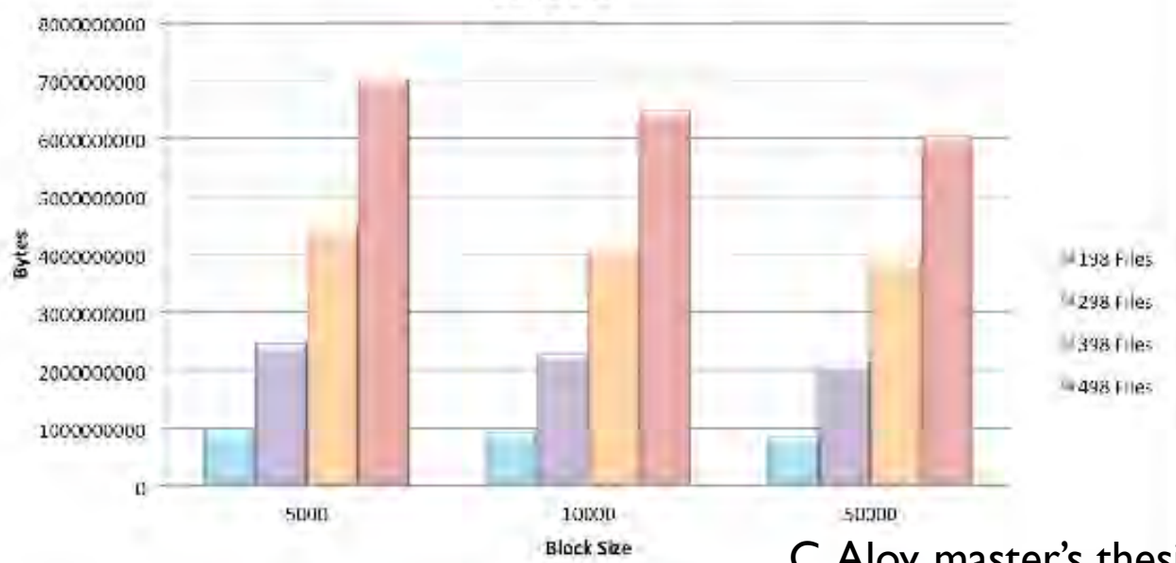
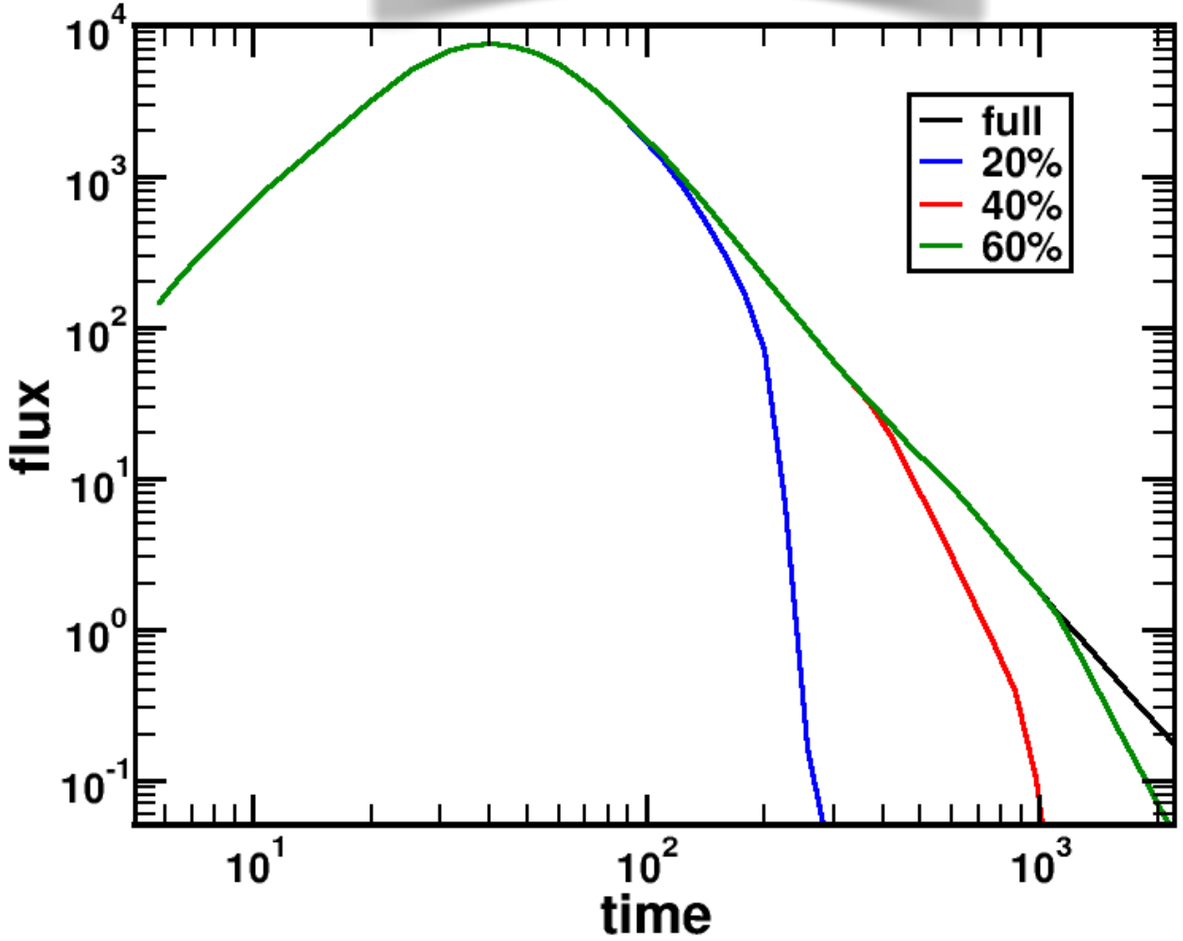


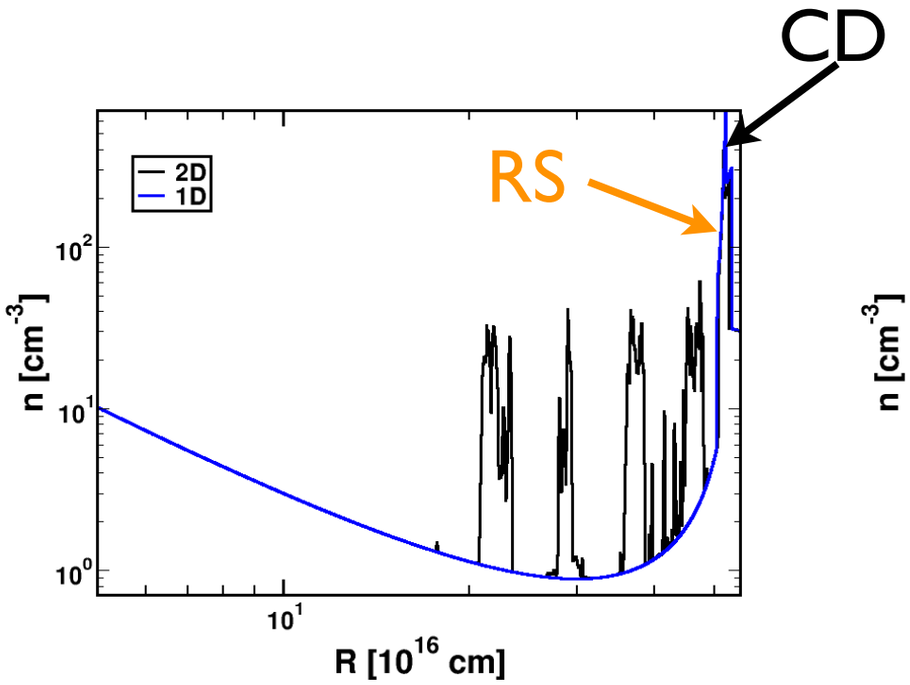
C. Aloy, master's thesis

Radio light curve

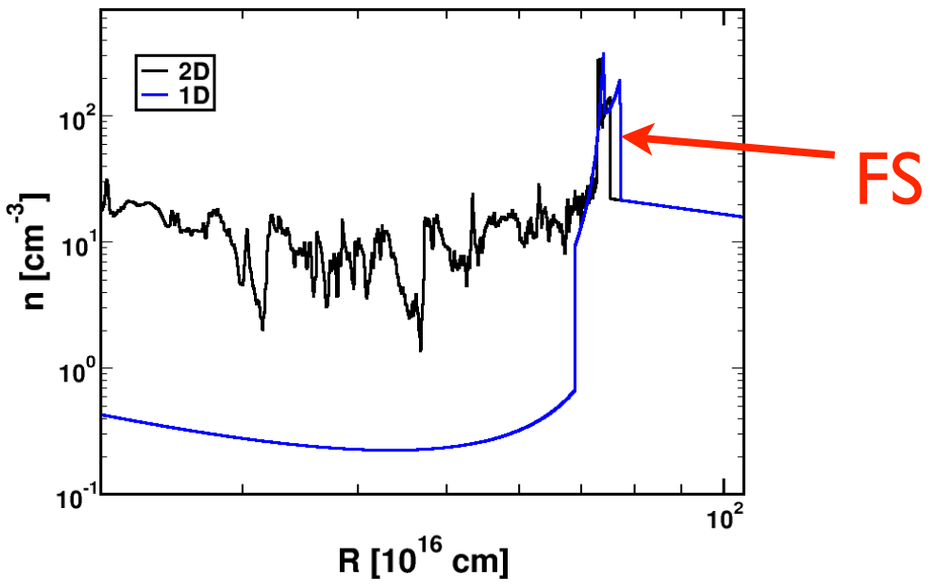


- 10^{6} non-thermal emitting regions (32 bins)
- enough space-time coverage is crucial for correct light curve computation
- extension of the duration of the light curve requires disproportionally more computation time and storage space!

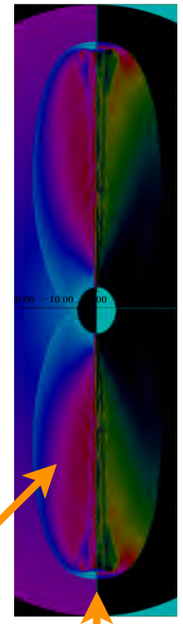
1D versus 2D



0.5 years



0.8 years



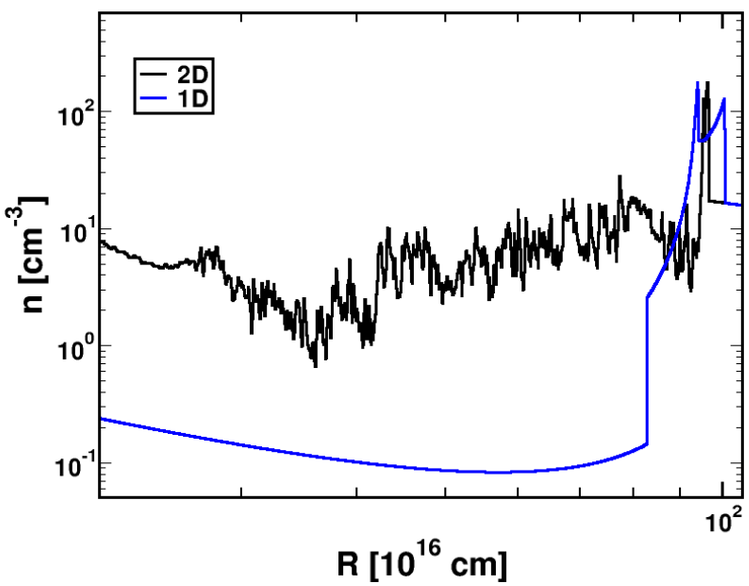
off-axis obs.

- radio maps, spectra
- light curves

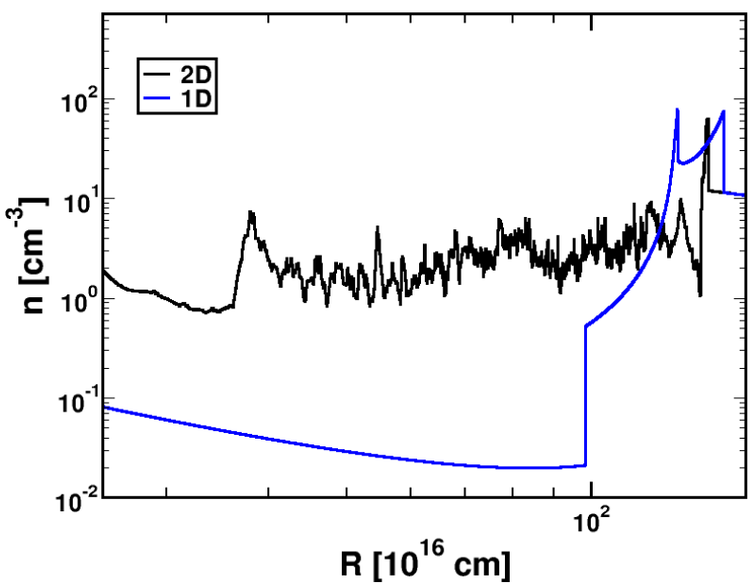
on-axis obs.

- 1D - 2D comparison
- comparison with J1644+57

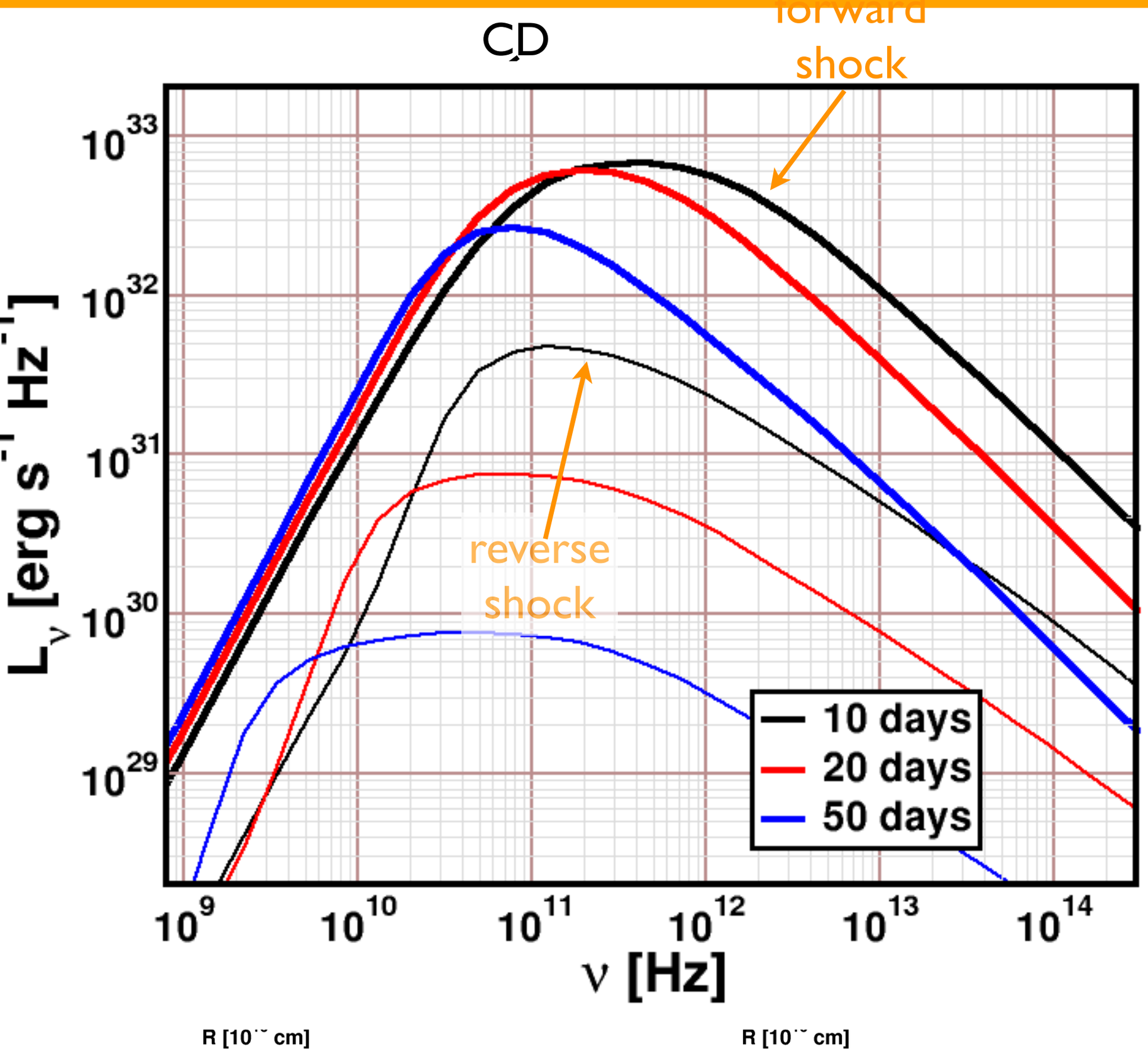
1 year

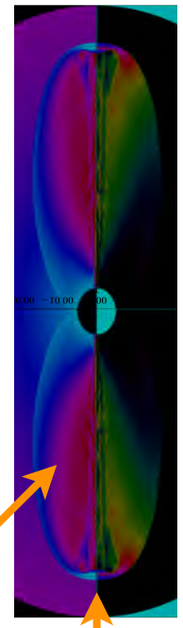


1.6 years



1D versus 2D





ectra

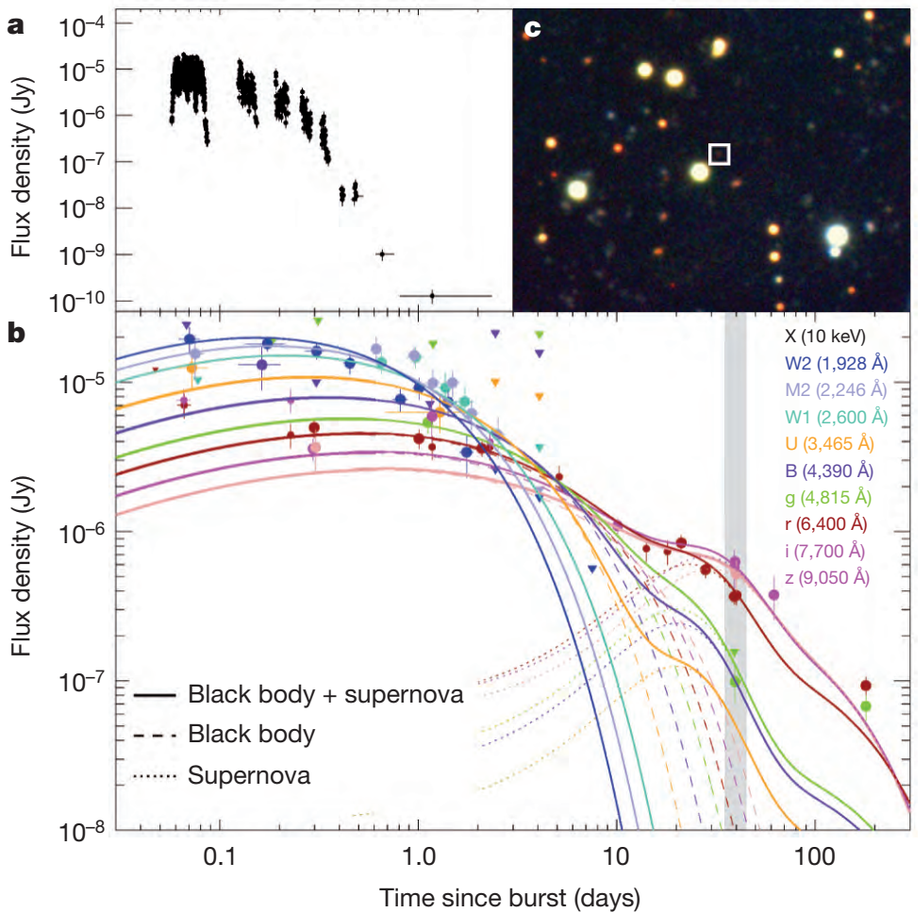
on-axis obs.

· 2D comparison
ıparison with J1644+57

GRB 101225A (BB dominated GRB)

Properties:

- Its γ-ray emission was exceptionally long-lived (T_{90} > 7000 s).
- It has no classical afterglow: the X-ray emission following the GRB is best fitted with **blackbody + power-law** spectrum



LETTER

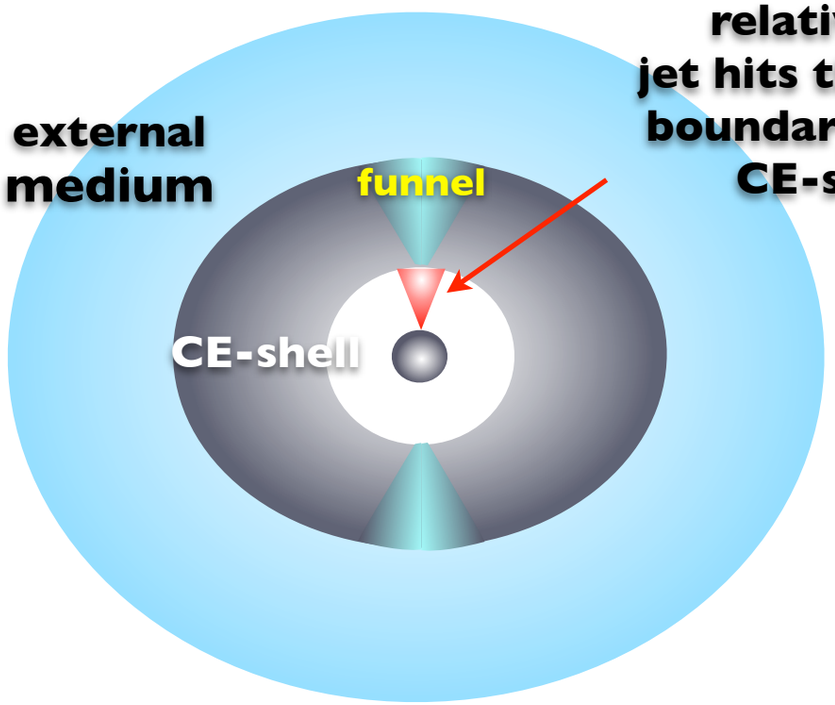
doi:10.1038/nature10611

The unusual γ-ray burst GRB 101225A from a helium star/neutron star merger at redshift 0.33

C. C. Thöne[1,2], A. de Ugarte Postigo[3], C. L. Fryer[4], K. L. Page[5], J. Gorosabel[1], M. A. Aloy[6], D. A. Perley[7], C. Kouveliotou[8], H. T. Janka[9], P. Mimica[6], J. L. Racusin[10], H. Krimm[10,11,12], J. Cummings[10], S. R. Oates[13], S. T. Holland[10,11,12], M. H. Siegel[14], M. De Pasquale[13], E. Sonbas[10,11,15], M. Im[16], W.-K. Park[16], D. A. Kann[17], S. Guziy[1,18], L. Hernández García[1], A. Llorente[19], K. Bundy[7], C. Choi[16], H. Jeong[20], H. Korhonen[21,22], P. Kubánek[1,23], J. Lim[24], A. Moskvitin[25], T. Muñoz-Darias[26], S. Pak[20] & I. Parrish[7]

Jet-shell interaction scenario

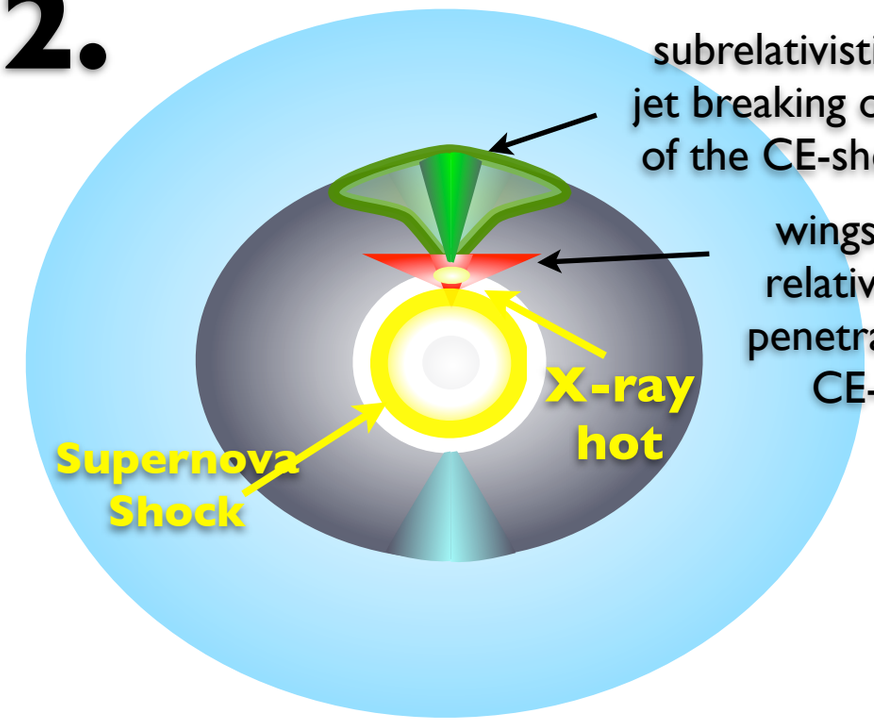
1.



relativistic jet hits the inner boundary of the CE-shell

About 4700 sec after the GRB

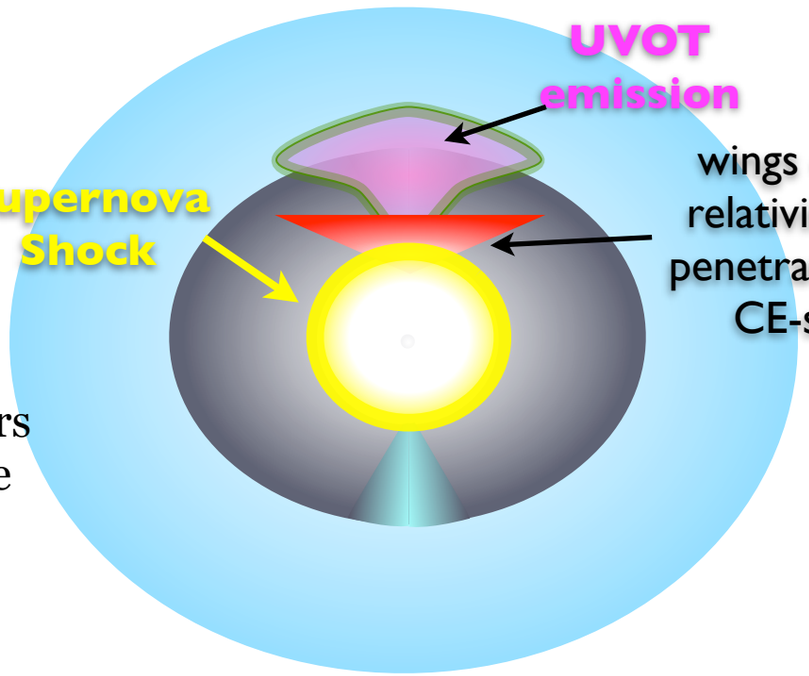
2.



subrelativistic jet breaking out of the CE-shell

wings of the relativistic jet penetrating the CE-shell

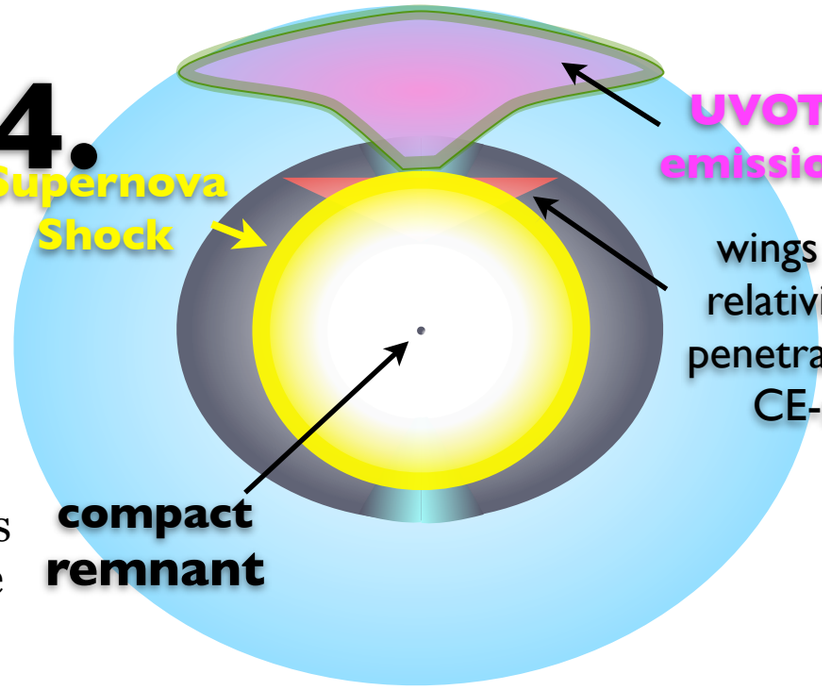
3.



wings of the relativistic jet penetrating the CE-shell

Few hours after the GRB

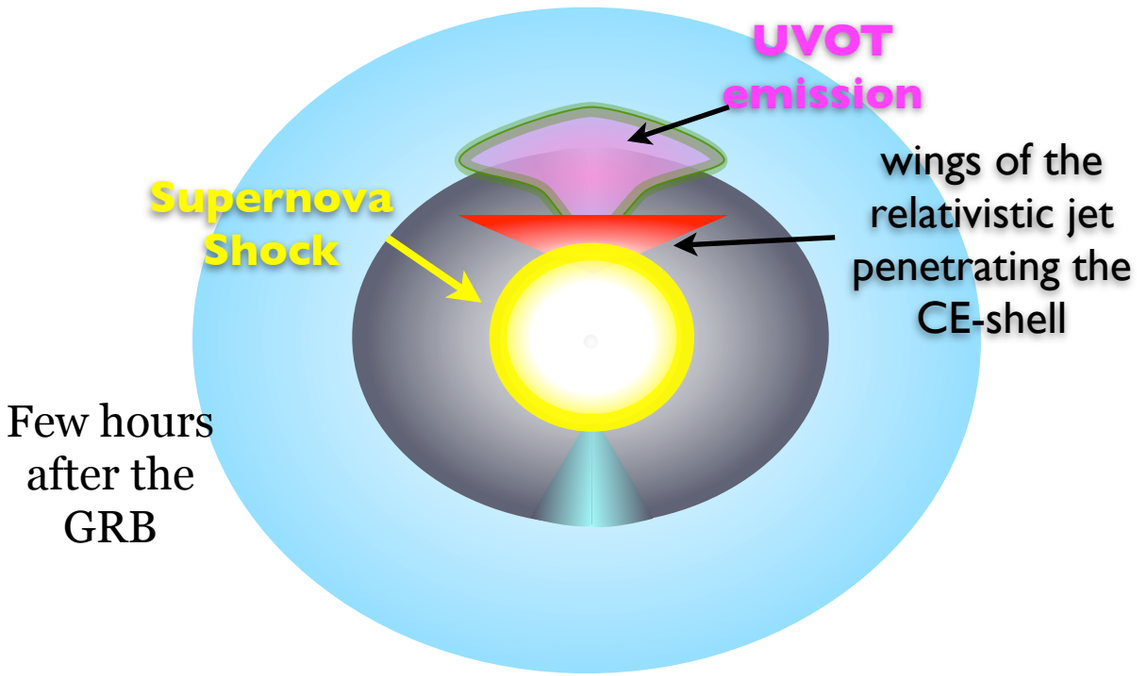
4.



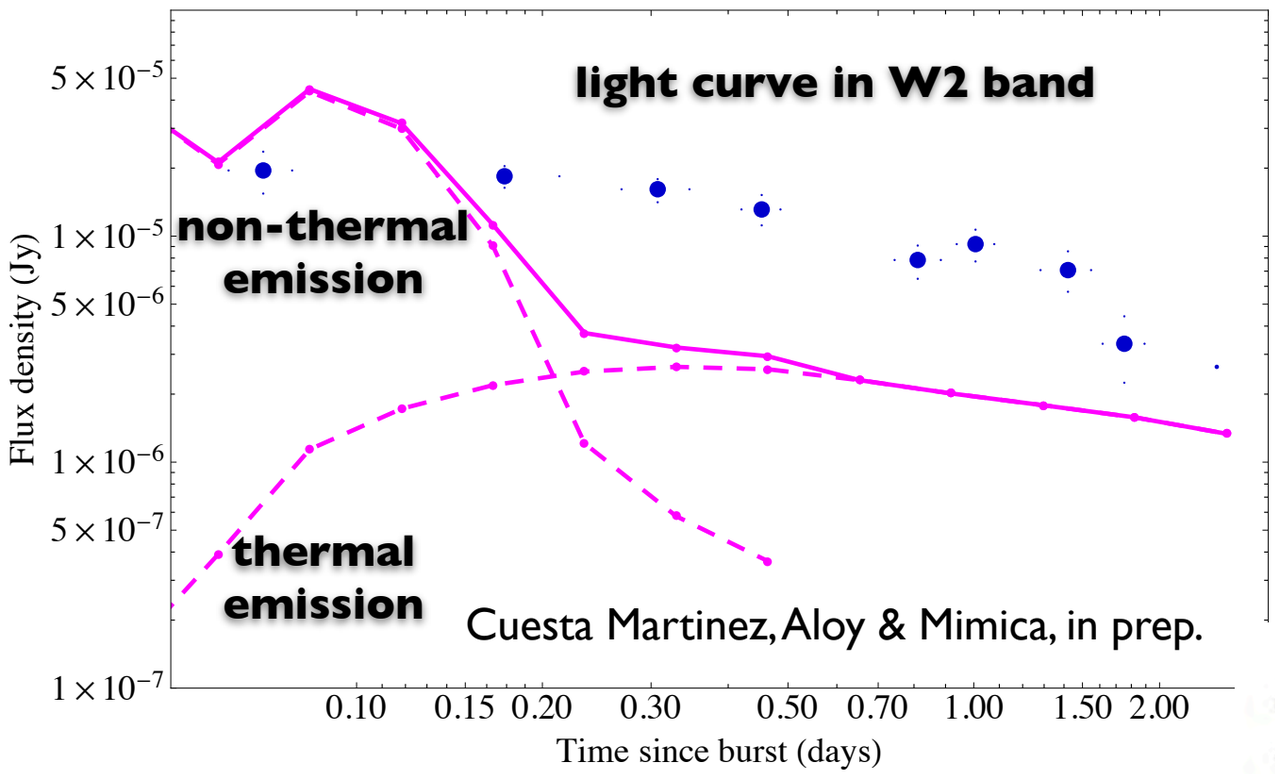
wings of the relativistic jet penetrating the CE-shell

Few days after the GRB

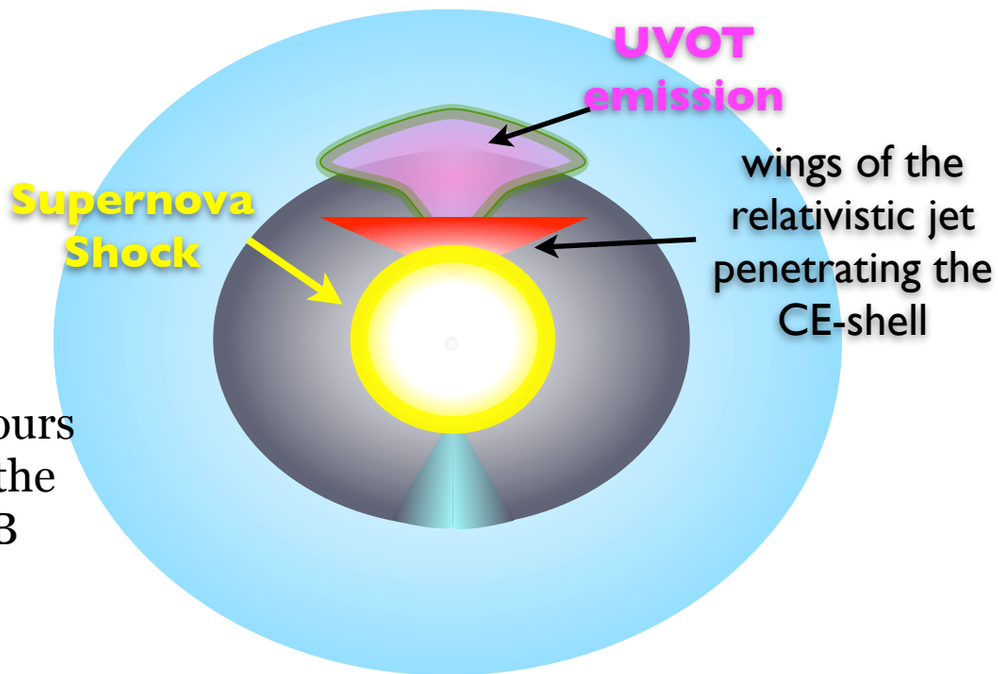
Thermal and non-thermal emission



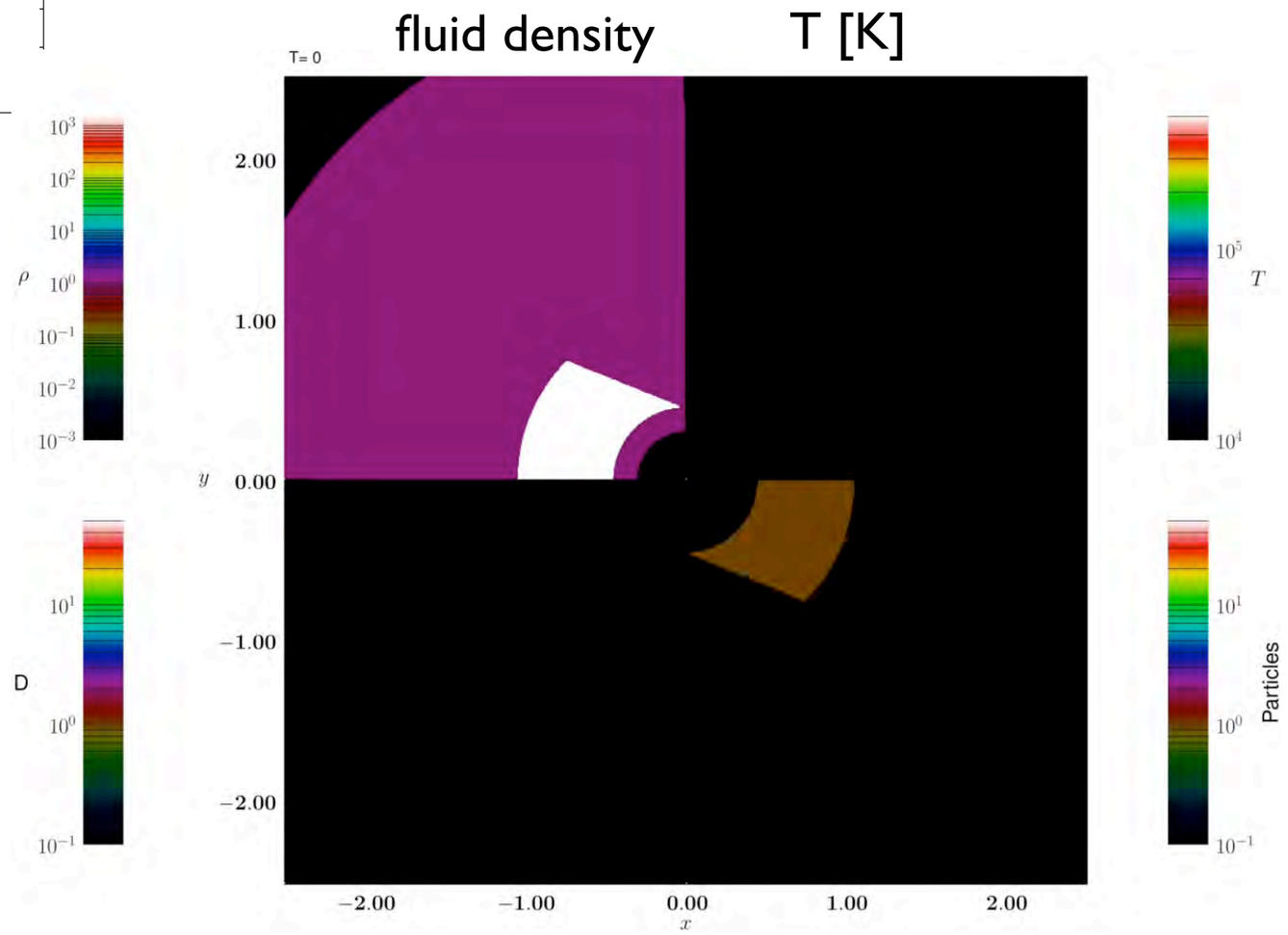
Thermal and non-thermal emission



- thermal emission: bremsstrahlung
- opacity: modified Kramers
- non-thermal emission: synchrotron
- non-thermal absorption: SSA
- source located at 0.33 <= z <= 0.85
- source observed on-axis



Few hours after the GRB



non-thermal thermal

Summary

- MRGENESIS+SPEV:
  - simulation framework applied to AGN, GRB and TDE jets
  - modular and adaptable to computing at different scales
- future development:
  - technical
    - go beyond the shared-memory parallelism for particles
    - improve I/O performance
    - multidimensional shock front reconstruction
  - modeling
    - improve non-thermal particle model
    - include polarization
    - radiative transfer in GR